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VAPOR-MODULATED HEAT PIPE REPORT

Contract NAS 2-8310

FLIGHT DATA ANALYSIS AND FURTHEP DEVELOPMENT OF VARIABLE-CONDUCTANCE HEAT PIPES

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1 0 INTRODUCTION

This report is on the development of a vapor-modulated heat pipe, which was carried out by TRW Systems Group under Contract NAS 2-8310 to Ames Research Center The heat pipe is a prototype for a typical spacecraft application The application in mind calls for heat loads up to 20 watts, a set-point temperature of 294K, and a sink that varies from -220K to nearly as high as the set-point The overall heat pipe length is 137 cm

Two basically different mechanisms of achieving variable conductance by vapor-flow throttling were studied In one, the thermal resistance between the heat source and sink is due to a saturation-temperature drop corresponding to the vapor-pressure drop developed across the valve This mechanism is the basis of the research heat pipe fabricated and tested under a previous contract NAS 2-5503 [1, 2] In the other, the pressure difference across the valve induces capillary groove and wick dry out in an evaporation region, and thus results in an increased thermal resistance This mechanism was selected for fabrication and test on the current contract In the next section, both mechanisms will be discussed in detail and the advantages of each compared

Section 3 0 presents the design of the prototype heat pipe In summary, it is a stainless-steel/methanol two-heat-pipe system The throttling valve is actuated by a bellows that is displaced by thermal expansion of liquid in an external sensor volume conductively coupled to the heat source When the source temperature falls below the set-point temperature, the valve closes and induces groove and wick dry out on the evaporation side of the interface between the two heat pipes The overall conductance decreases and therefore the temperature of the source increases Conversely, when the source temperature rises above the set-point, the valve opens and the dryed-out wick and grooves re-wet The overall conductance is restored to a high value which decreases the source temperature

In Section 4 0, the test of the heat pipe is described and the results are discussed The test successfully demonstrated the control mechanism, but also pointed to some needed design improvements In particular, the capacity of the heat pipe was below the design goal, the set-point was affected by the sink temperature, and the heat-source temperature tended to over- and under-shoot the set-point Under one operating condition, a steady-state oscillation of the sensor-volume temperature occurred Noncondensable gas generation was a problem during testing, however subsequently the heat pipe was run continuously until gas generation went to completion With the heat pipe free of noncondensable gas, a high conductance was achieved with the valve fully open The overall temperature drop between the evaporator and condenser is 0 084°C/watt, which corresponds to heat-transfer coefficients in excess of 1,300 BTU/hr-ft^2-°F on each side of the heat pipe interface

2 0 MECHANISMS OF VAPOR-MODULATED CONTROL

2 1 VARIABLE CONDUCTANCE BY INDUCED DROP IN SATURATION TEMPERATURE

Consider, as shown in Figure 2-1, a vapor-modulated heat pipe where variable conductance is achieved by inducing a drop in the saturation temperature When the evaporator region falls below the set-point, the fluid in the control volume contracts and the valve closes The increased pressure drop across the valve corresponds to an increase in the saturation temperature, which results in the evaporator temperature rising Conversely, when the evaporator rises above the set-point, the valve opens and the saturation temperature drop decreases, which results in the evaporator temperature lowering The water/monel heat pipe of this type that was developed on the previous contract [1] demonstrated good control characteristics A control range of 2 2°C was achieved for large variations in sink temperature and heat load

2 2 LIMITATION OF SATURATION TEMPERATURE DROP MECHANISM

The primary limitation of the saturation-temperature-drop mechanism is that the maximum drop that can be achieved is set by the capillary-pressure limit of the wick Once the pressure drop exceeds the wick's limit, vapor "blows through" where the wick penetrates the valve bulkhead For example, the pore size of the wick required to prevent blow through when the fluid on the condenser side is at 220K and the fluid on the evaporator side is at 294K is given in Table 2 1 With the exception of water, the fluid/wick combinations listed in Table 2 1 have low heat-transfer capabilities Unfortunately, water must be ruled out for applications where the condenser side falls below 273K because the water would freeze out in the condenser

Two approaches can be taken to increase capacity First, as in the case of the water/monel research heat pipe, an artery can be used The disadvantage of this approach, however, is the problem of arterial priming without trapping a bubble of residual noncondensable gas Priming foils [3] offer a practical solution only for pore sizes down to approximately 0 013 cm For smaller pores, the foil must be impractically thin The second approach to increase capacity is to make the

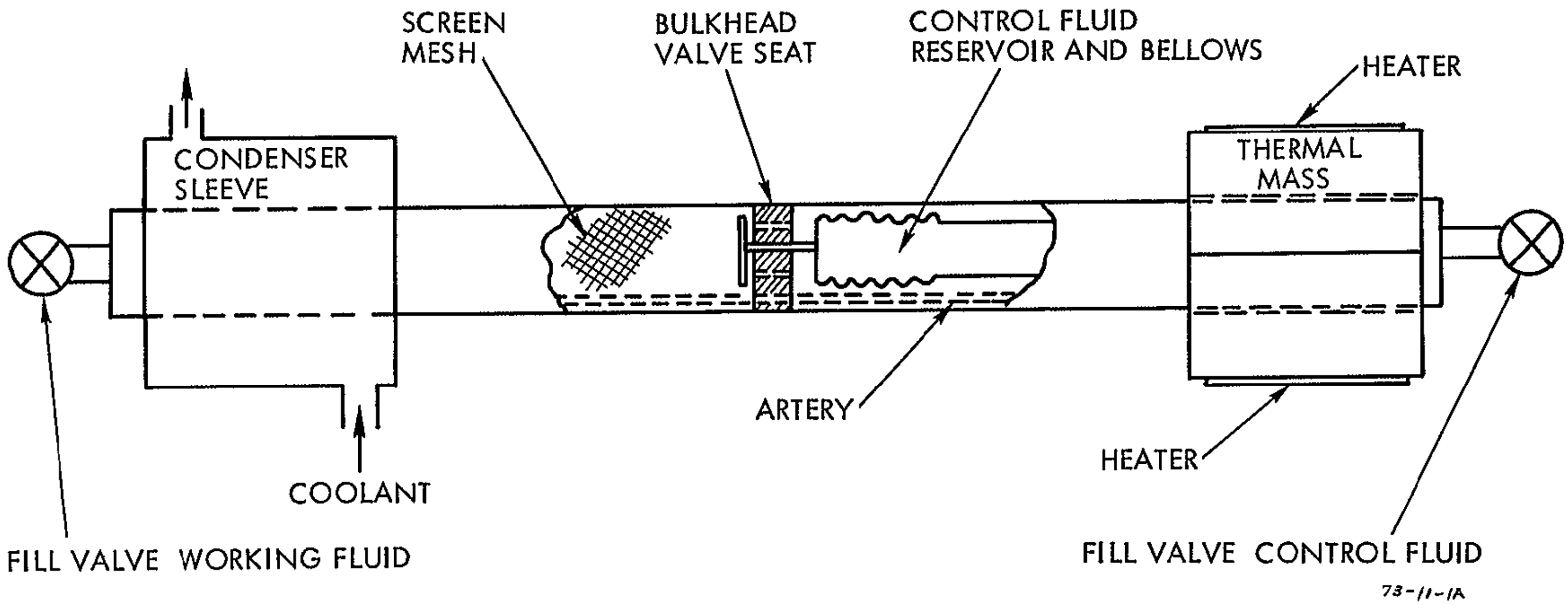

FIGURE 2-1. Vapor-Modulated Heat Pipe with Control Achieved by Drop in Saturation-Temperature.

Table 2.1 Fluid-Wick Combinations for Vapor-Modulated Heat Pipe

FLUID	VAPOR PRESSURE AT 294K	WICK PORE DIAMETER TO PREVENT BLOW-THRU*	HEAT PIPE FIG OF MERIT	FREEZING TEMP
Ammonia	6720 torr	1 44 x 10^{-5} cm	70 x 10^9 w/m^2	195K
Methanol	100 8	0 00067	37 x 10^9	175
Water	18 97	0 01146	180 x 10^9	273
Isopropyl Alcohol	32 88	0 00198	5 26 x 10^9	187
Isobutyl Alcohol	9 28	0 00688	3 03 x 10^9	165
Isoamyl Alcohol	2.509	0 0279	2 85 x 10^9	156
Octane	10 71	0 00609	10 15 x 10^9	216
Nonane	3 46	0 0177	7 47 x 10^9	219

*Evaporator Temperature = 294K, Condenser Temperature = 220K vapor-modulated heat pipe as short as possible and use it as a variable-conductance coupler between two conventional heat pipes The disadvantage of a three-heat-pipe system, though, is the increased temperature drop due to two additional evaporation surfaces and two additional condensation surfaces

2 3 CONTROL BY INDUCED WICK/GROOVE DRY OUT

Figure 2-2 shows a vapor-modulated heat pipe where variable conductance is achieved by drying out the wick and grooves on the high-pressure side of the valve When the valve closes in response to the sensor-volume temperature falling below the set-point, the pressure P_{v_1} increases relative to the liquid pressure P_{ℓ_1} until it is in excess of the capillary-pressure limit of the wick and grooves As a result, the liquid flows through the bulkhead and the evaporator side of the bulkhead drys out Mathematically, the vapor-liquid pressure difference $\Delta P_{v_1} - P_{\ell_1}$ is calculated by equating the pressure drops along the dotted line circuit in Figure 2-2 to zero Pressure variations in the vapor on each side of the valve are assumed to be negligible, however, the pressure drop across the valve is ΔP_v At the condenser end, we assume no difference between the liquid pressure P_{ℓ_1} and the vapor pressure P_{v_1} The average vapor-liquid pressure difference on the evaporator side of the bulkhead is, then,

$$\Delta P_{v_\ell} = \Delta P_\ell + \Delta P_v \qquad [1]$$

where ΔP_ℓ is the liquid pressure drop in the wick. The liquid pressure drop depends on the heat transfer-rate and also the sink temperature, since it sets the value of the liquid viscosity Assume that at maximum heat load and the lowest sink conditions, ΔP_ℓ is less than the capillary pressure P_c' required to reprime the wick structure Thus we are assured that when the valve is open and $\Delta P_v \approx 0$, the entire wick structure will be primed and the overall thermal resistance will be minimum When the valve closes, the pressure difference builds up until $\Delta P_v + \Delta P_\ell$ exceeds the capillary pressure P_c required to empty the wick structure, and liquid flows out of the evaporator-side wick structure To ensure that the structure completely drys out, the wicks on the evaporator and condenser side of the bulkhead are separated by a

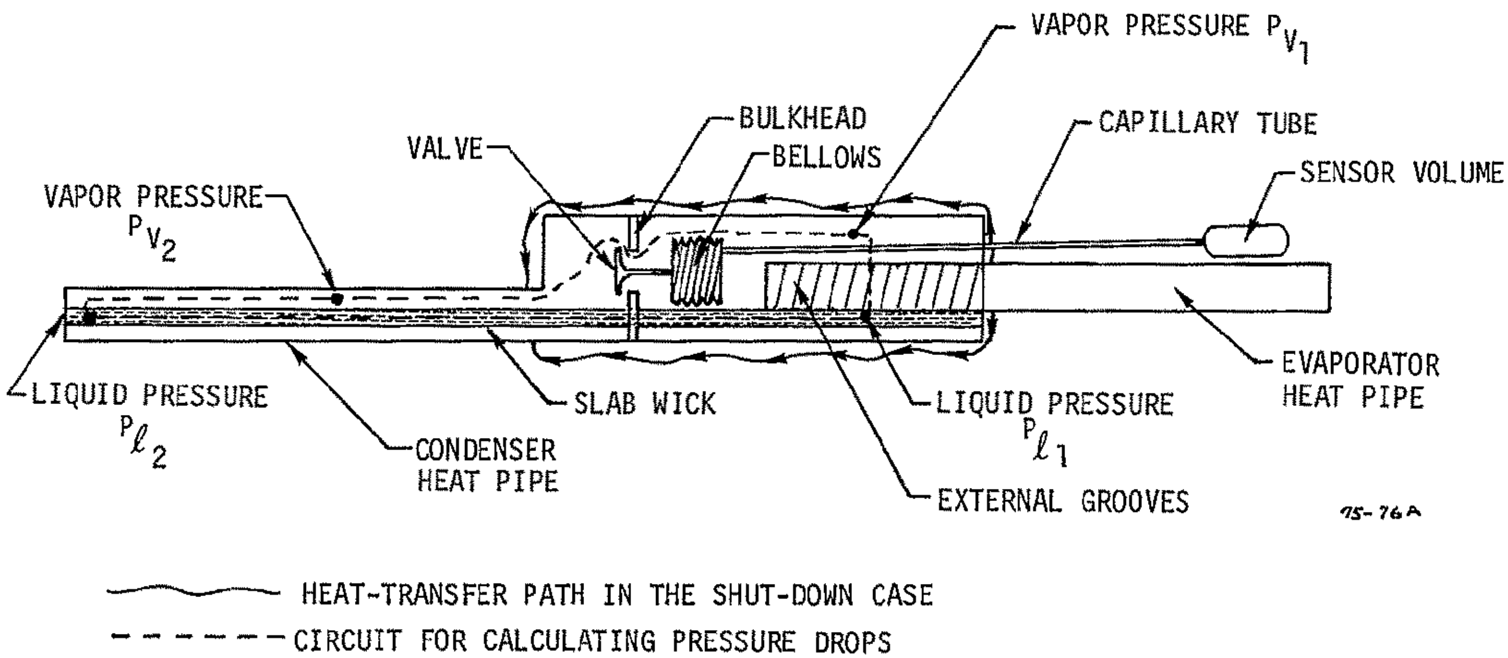

FIGURE 2-2. Vapor Modulated Heat Pipe with Control Achieved by Inducing Wick/Groove Dry Out.

local high-capillary-limit region that we call a "capillary barrier " Before the capillary barrier blows through, a vapor-liquid pressure difference is generated well in excess of that required to dry out the evaporator-side wicking Further, with the valve closed, if blow through does occur and the pressures on each side of the bulkhead equalizes, the capillary barrier will reprime and re-establish isolation before the wick/groove structure reprimes

In steady-state operation, the valve operates in a partially-closed position, and the resulting pressure drop produces just enough wick/groove dry out to hold the source temperature at the set-point First, the grooves begin to dry out since they are designed to have a lower capillary-pressure limit than the wick As the valve closes further, progressively more of the grooves dry out Then the wick begins to dry out from its end When the valve is fully closed, the wick completely dries out

Using two heat pipes for the system serves two purposes First, if only one heat pipe were used, regions of the evaporator that are dried out could become hot if the heat source in that region is dissipative A two-heat-pipe system ensures that the evaporator region remains isothermal Second, with two heat pipes, there is a minimum length of dryed out wick to reprime when the valve opens Thus, the characteristic time for repriming is kept small compared to the thermal time constant, which lessens the possibility of oscillations, over-shoots and under-shoots

2 4 ADVANTAGE OF INDUCED-DRY-OUT MECHANISM

The primary advantage of the dry-out mechanism over the saturation temperature drop mechanism is that there is no restriction to low pressure fluids For example, ammonia and methanol, which are both good heat-pipe fluids, must be ruled out for saturation-temperature-drop control The pressure drop corresponding to a saturated temperature difference of 74K, for example, is too large to be sustained by a practical wick structure Blow-through is not a problem for the dry-out mechanism because dry out is complete when blow-through occurs Another advantage of the dry-out mechanism is that it has a higher thermal impedance in shut-off operation With the wick completely dryed out, the heat-leak path is as shown in Figure 2-2 For the saturation-temperature-drop mechanism, the heat-leak path is directly through the bulkhead

3 0 DESIGN

3 1 PRELIMINARY DESIGN BASED ON SATURATION TEMPERATURE DROP

The first design considered was based on the mechanism of saturation temperature drop Although it was eventually rejected, we briefly discuss it here because it led to the dry-out mechanism The design began with a search for the best working fluid. The properties sought were

- Freezing point below 220F
- Practical wick pore size (>0 01 cm) that will prevent blow-through in the cold-sink conditions
- Highest possible figure of merit

Referring to Table 2 1, we see that nonane is the best candidate Its figure of merit is low, though, so a three-heat-pipe system was selected Nonane would be used only in a 20-cm long vapor-modulated coupling section X-13 felt metal was selected as the wick, and its capacity with nonane is predicted to be 294 watt-in per square cm of wick area To attain a capacity of 26 watts, the cross-sectional area was taken as 0 90 cm^2 Some increase in performance is attained by shunting the wick on the condenser side of the bulkhead with open-ended screen tubes

The capacity prediction for X-13 metal felt and nonane was verified with the test of a simple circumferentially grooved, slab-wick heat pipe Although the measured axial transport of the wick agreed with the theory, the circumferential grooves (40/cm) dried out Clearly, the capillary limit of the grooves was far lower than the wick Much finer grooves could be fabricated for the actual vapor-modulated heat pipe, and our predictions showed the groove performance would be adequate if the valve were fully open With the valve partially closed, however, the grooves would not function because of the increased vapor–liquid pressure difference imposed by the pressure drop across the valve This was of concern until we realized that the temperature drop associated with groove failure was in addition to the saturation temperature drop across the valve, that is, groove dry out enhances the control mechanism It was then realized that the saturation temperature drop was not needed at all if one designed for both groove and wick dry out when the valve closed Because of nonane's low figure of merit, it was decided to switch to a methanol heat pipe with the new control mechanism

3 2 DESIGN BASED ON INDUCED WICK/GROOVE DRY OUT

The design of the heat pipe that was fabricated and tested is most clearly shown in SK740903 in the Appendix The most important features of the design, the bellows/valve subassembly and the wick feed-through, are discussed below

3 2 1 The Bellows/Valve Subassembly

The bellows/valve subassembly is shown in SK740907 and also in the photograph of Figure 3-1 The bellows is welded into a machined can, thus the control fluid is on the outside of the bellows and compresses it upon expansion The can is held in place by three posts that also serve as valve guides The valve is held in place by the conical return spring The valve stem is not connected to the bellows so in the closed position the spring causes automatic seating alignment

The sensor volume is shown in SK750310E Another bellows that is identical to the one that actuates the valve is welded into the end of the sensor volume Its extension is adjusted with a screw to provide convenient set-point adjustment The sensor volume contains 2 2 cc of liquid Perfloro-pentane was selected as the control liquid because of its high coefficient of thermal expansion (2 06 x $10^{-3}/°C$) The displacement ΔX of the valve for a temperature change ΔT of the control liquid in the reservoir of volume V_ℓ is given by

$$\Delta X/\Delta T = \beta\Delta T/(A/V_\ell + \alpha K/A) = 0\ 141 \text{ mm/°C}$$

where

β = 2 06 x $10^{-3}/°C$ at 25°C is the thermal expansion coefficient,

A = 0 316 cm^2 is the effective area of the bellows,

K = 23 3 N/cm is the spring constant of the system, and

α = 3 24 x 10^{-5} cm^2/N is the compressibility at 25°C

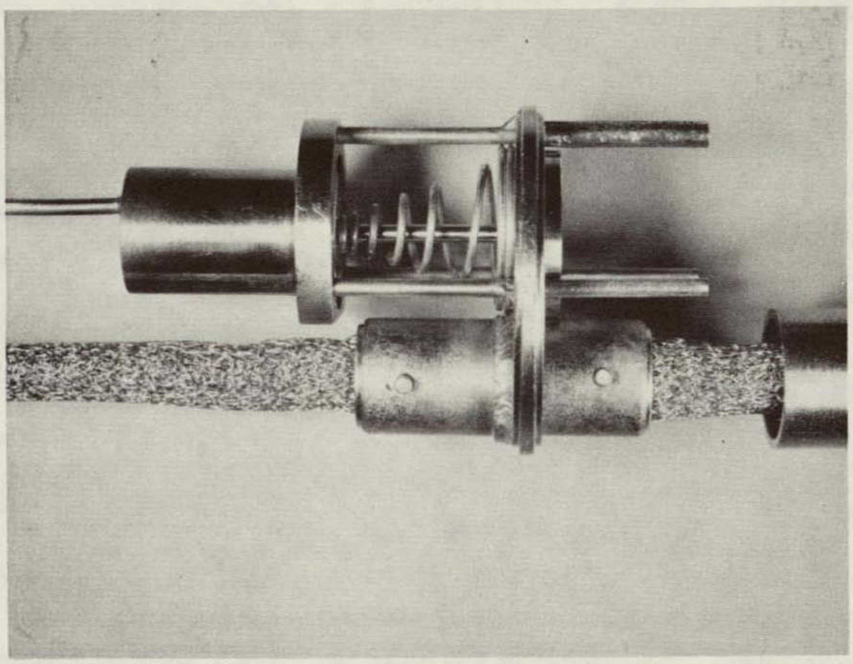

FIGURE 3-1. Bellow/Valve Subassembly and the Wick Feed-Through.

The pressure drop ΔP across the valve is derived from the model depicted in Figure 3-2 The resulting expression in terms of the heat transfer rate Q, latent heat h_{fg}, vapor density ΔP, valve diameter D, valve opening ΔX and contraction coefficient C_c is

$$\Delta P = \frac{1}{2\rho} \left[\frac{Q}{h_{fg}\pi D \Delta X C_c}\right]^2 .$$

For methanol at 294K and for a heat-transfer rate of 50 watts, we find that the pressure drop is approximately 1 mm of methanol for a valve opening of 0 75 mm We take this as the fully open displacement, since 1 mm of methanol is small compared to the capillary pressure generated by the wick and grooves The valve goes from completely closed to fully open when the sensor-volume temperature increases 5 3°C This temperature excursion is then the approximate control range of the heat pipe.

The bellows is protected from damage from liquid expansion for temperatures above the set point For example, the valve opening at 30°C above the set point is 3 8 mm, at which point the bellows is still not bottomed out

3 2 2 <u>The Wick Feed-Through</u>

The wick feed-through is shown in the subassembly drawing SK740910 and also the photograph of Figure 3-1 The capillary barrier consists of two layers of 250-mesh stainless-steel screen, which is sintered between the two wick-tunnel tubes This sintered assembly is welded into a hole in the bulkhead The two ends of the wick are formed into a round cross section and pinned into the two wick clamps The wick is cut square, pressed against the capillary screen and pinned in place A disc of X-7 stainless steel felt metal 0 254 mm thick was placed inside the wick tunnel on each side of the screen when cracks in the screen were found after the wick tunnel was welded into the bulkhead

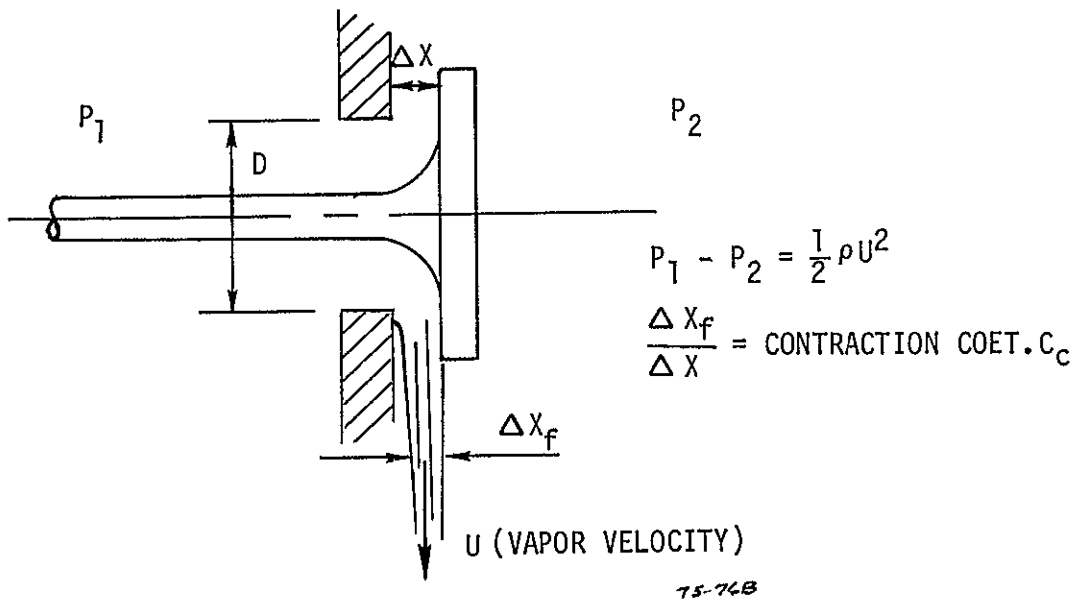

FIGURE 3-2. Model for Calculating Pressure Drop Across Valve

4 0 TEST RESULTS

4 1 INSTRUMENTATION

The heat pipe was instrumented with thermocouples as shown in SK750324E The condenser was clamped to a cold plate with saddle blocks The evaporator and sensor volume were clamped between two aluminum blocks having double saddles Strip heaters were used on the outside of these blocks To simulate a thermal resistance between a heat pipe and the equipment whose temperature is being controlled, 0 006 inches of teflon were used between the heat pipe and the heater blocks The sensor volume, on the other hand, was thermally close-coupled to the heater blocks with RTV

4 2 INITIAL TEST

For the initial test (Figure 4-1) the sink was raised to 100F with no power on the heat pipe When the temperatures along the heat pipe were all above 90F, the valve was presumed open [The system was set so the valve would close at 70F and be open (0 76 mm) at 80F] At 14 03, 10 watts were applied to the pipe and the sink temperature was dropped The temperatures along the heat pipe dropped along with the sink until 14 31 when the sensor volume reached 70F where the valve closed The sink temperature continued to drop to 33F and after a few damped oscillations the sensor volume temperature stabilized at 75F The sink was then raised in temperature until the sensor volume was above 90F and the valve open

The initial test verified that the bellows-valve system was working properly A temperature gradient was apparent in the condenser heat pipe, however, which indicates the presence of noncondensable gas The effect of the gas is seen in Figure 4-1 by the increasing temperature difference between the condenser wall vapor and the sink as the sink temperature dropped Also apparent is a 5F temperature drop between the vapor in the evaporator and condenser heat pipes when the valve was fully open (see data at 15 46) This is larger than expected and is probably due to either excess liquid blockage or gas in the evaporator heat pipe The

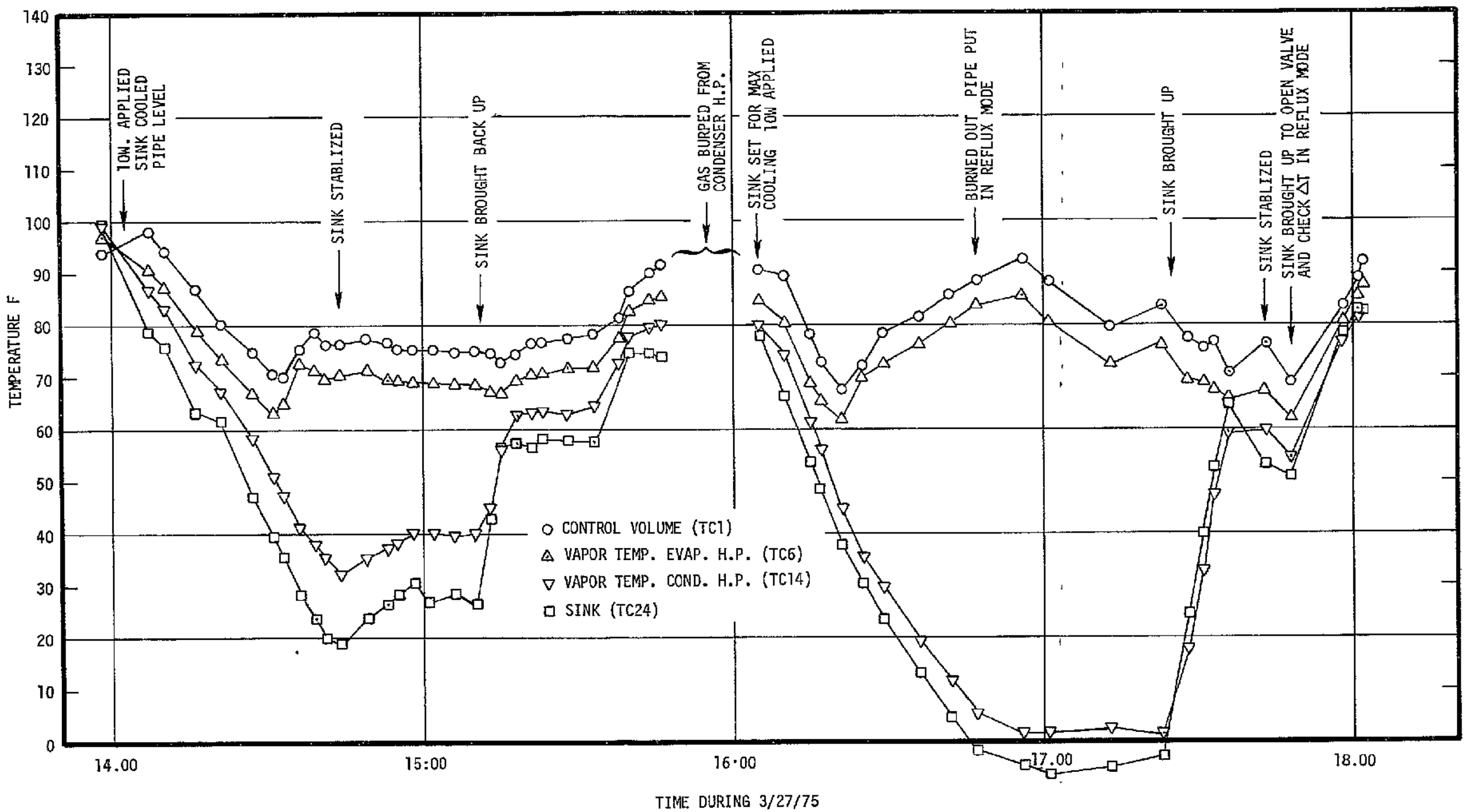

FIGURE 4-1. Initial Test of Vapor-Modulated Heat Pipe.

FOLDOUT FRAME

FOLDOUT FRAME 2

presence of gas is believed to result from not vacuum firing at high temperature (1800F) which is part of our normal cleaning procedure for methanol/stainless-steel heat pipes The vacuum firing was eliminated so the bellows and valve-return spring would not anneal An earlier test on the CTS program showed that eliminating vacuum firing does result in gas generation. Subsequent to testing the heat pipe was run continuously at 100F and gas-generation mechanisms went to completion

Before running the second test, the gas was vented from the condenser heat pipe At 16 05 (Figure 4-1), the heat sink was dropped in temperature with 10 watts applied to the heat pipe Without gas, the condenser heat pipe was nearly isothermal Note the condenser-to-sink temperature drop is much smaller than the first test When the control volume temperature reached 68F, the valve closed and the temperature began to rise as the wick and grooves on the high pressure side of the valve dryed out As the valve reopened, however, the wick did not reprime, which was the first indication that the heat pipe capacity was lower than expected By 16 47 the control volume temperature rose to 88F The condenser end of the heat pipe was raised approximately 3 inches higher than the evaporator at 16 47 in a partially successful attempt to recover control The temperature began to decrease but it did not return to the control range Recovery was achieved only when the sink was brought back up in temperature

4 3 CAPACITY TEST

The fact that the heat pipe did not recover even in a reflux mode suggests that the liquid fill was marginal and contraction at lower temperatures starved the wick An additional 5 cc of methanol was added to the condenser heat pipe and a capacity test was carried out with the heat pipe at 0 1 in heat pipe mode The control volume was held at 100F by adjusting the sink temperature which ensures that the valve is fully open As shown in Figure 4-2, the heat input was increased in 5-watt increments until the temperature difference between the vapor in the evaporator and condenser heat pipes increased rapidly This is due to the grooves at the coupling of the heat pipes drying out under load The heat input was then decreased in 5-watt increments until the heat pipe

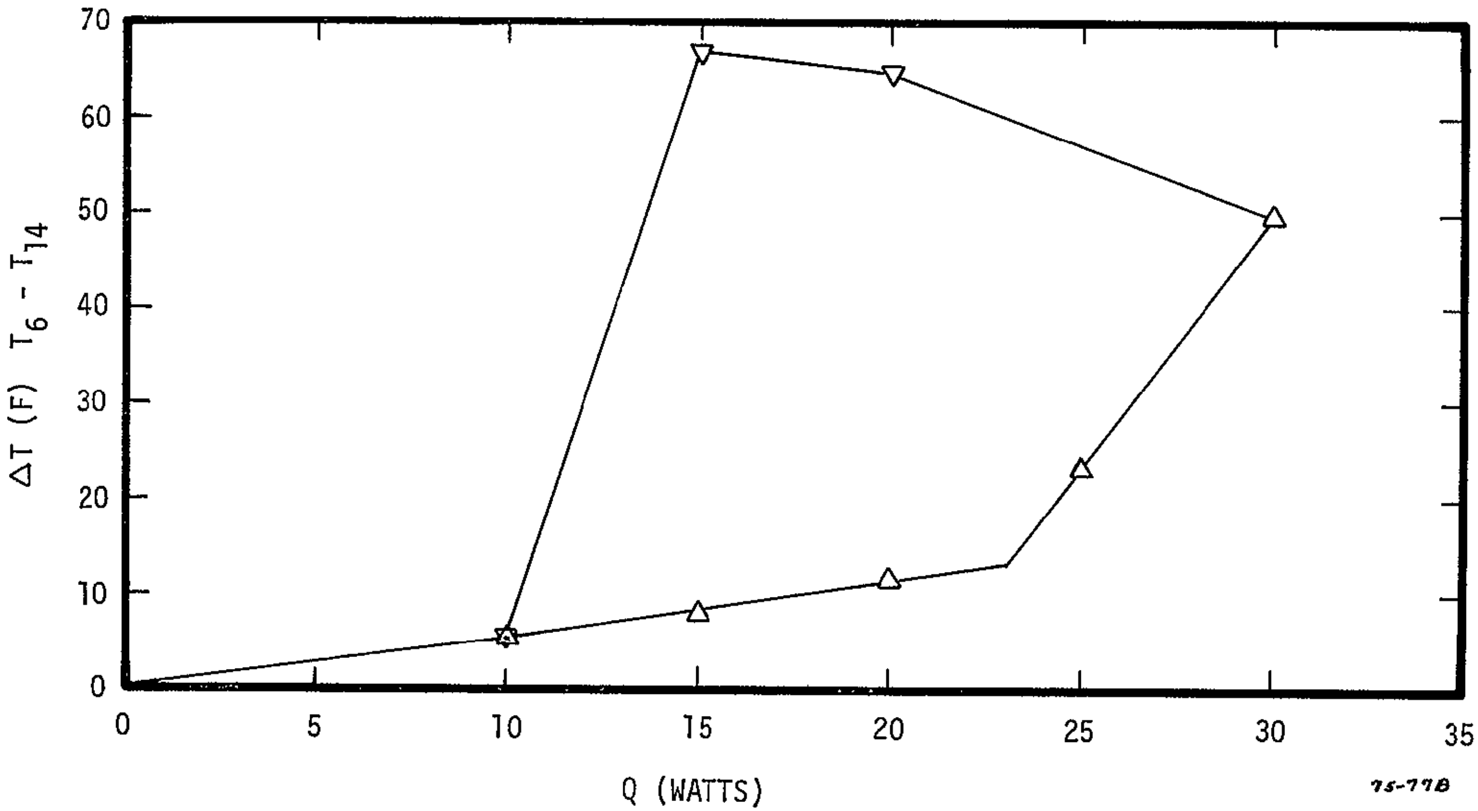

FIGURE 4-2 Vapor Modulated Heat-Pipe Capacity Tests.

recovered, which did not occur until the power was reduced to 10 w This result is in line with the hysteresis behavior of fibrous wicks, that is, the capillary-pressure limit for a wick on the verge of emptying is twice that for priming a wick [4] The predicted open-valve capacity was approximately 50 watts for the wick emptying and thus 25 watts for repriming under load The fact that the measured capacity was 50% lower than predicted is attributed to two factors

1 The flow resistance in the feed-through was neglected in the predictions In fact, the original design which called for a capillary barrier of two layers of 250-mesh screen had to be modified by adding two 0 254 mm layers of X-7 felt metal on either side of the screens, which had developed cracks during welding.

2 The predictions were based on wick failure, however, the ΔT first rises rapidly when the grooves fail For purposes of control, the grooves were intentionally designed to fail first

After the capacity test, the question remained as to whether after the addition of 5 cc of methanol, there was sufficient liquid in the condenser heat pipe. With 10 w on the heat pipe and the evaporator elevated 0 1 inch, there was a 4 3F overall temperature drop in the condenser which reduced to 1 2F when the heat pipe was put in a reflux mode This is clear evidence that the temperature drop is due to excess liquid, and therefore we concluded there was sufficient liquid in the heat pipe

Attention was next turned to the open valve temperature drop between the two heat pipes The slope of ΔT versus Q in Figure 4-2 corresponds to a combined condensation, conduction and evaporation heat transfer coefficient at the interface between the two pipes of only 185 BTU/hr-°F-ft^2 This low value could be due to excess liquid and/or gas in the evaporator heat pipe Therefore, 2 29 cc of methanol were removed and any possible gas was vented The measured overall heat transfer coefficient increased to 603 BTU/hr-°F-ft^2, which is a high value for methanol and stainless steel. The low heat transfer coefficient was probably due primarily to gas, because after venting it again degraded slowly with time The temperature profiles along the heat pipe with the valve full open is shown by curve (a) in Figure 4-3

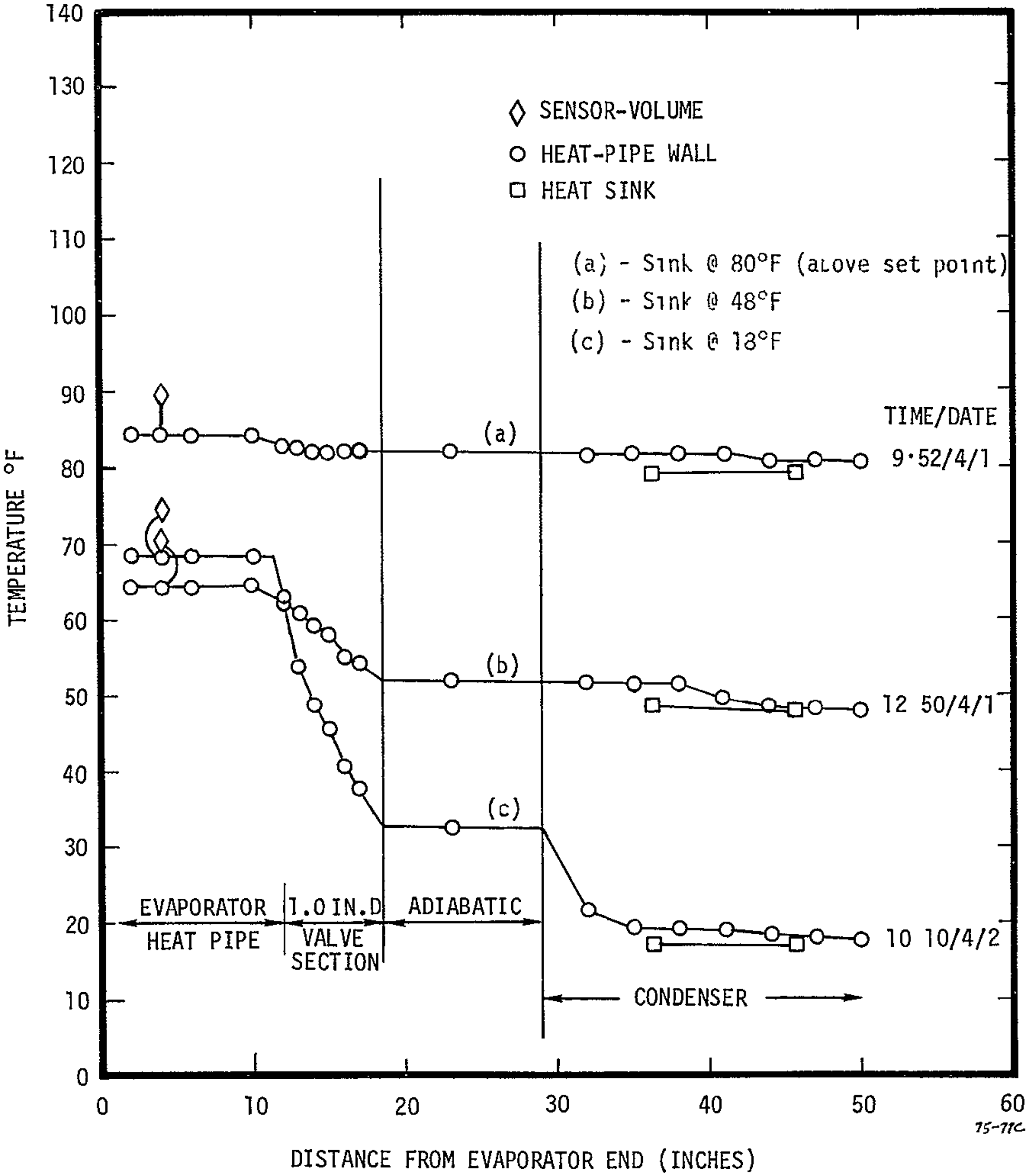

FIGURE 4-3 Temperature Distribution Along Heat Pipe.

4 4 SHUT-DOWN HEAT LEAK

We next investigated the minimum power for which the set point could be maintained. Ideally, this minimum power equals the heat leak down the pipe With the valve fully shut off, the heat-leak path is from the evaporator heat pipe to the condenser heat pipe through the wall and end plates of the valve section The sink was set at 40F, and the power at 10 w The power was then reduced in steps to 3 w, 1 w, and finally 0 w The heat pipe never went below the set point Evidently, the heat leak into the evaporator heat pipe through the insulation was greater than the heat leak down the heat pipe

4 5 PERFORMANCE CHARACTERISTICS

The next series of tests, displayed in Figure 4-4 was a systematic exploration of the heat-pipe characteristics The power was varied in steps for three sink conditions, 50F, 30F and -20F Note that at 5 w the temperature of the sensor volume does not reach a steady state Data taken every minute shows a steady regular oscillation, for example, data taken at 16 00 on 4/1/75 Two time lags are thought to govern the oscillations, the time it takes for the sensor-volume liquid to change temperature in response to the evaporator heat pipe vapor temperature and the repriming time when the valve opens At higher powers, no oscillations occur

At a 40F sink condition the sensor-volume temperature increases with increasing power up to 15 w, then at 20 w burnout occurs The reason for the set-point increase is that groove dry out is induced by liquid-flow pressure drop as well as vapor throttling Thus, an increase in power increases the liquid-flow pressure drop, which in turn, increases the groove dry out and temperature difference between the heat pipes As a result, the control-volume temperature rises until the valve opens sufficiently to allow the grooves to recover from the liquid-flow-induced dry-out The change in set point as a function of heat load is displayed in Figure 4-5

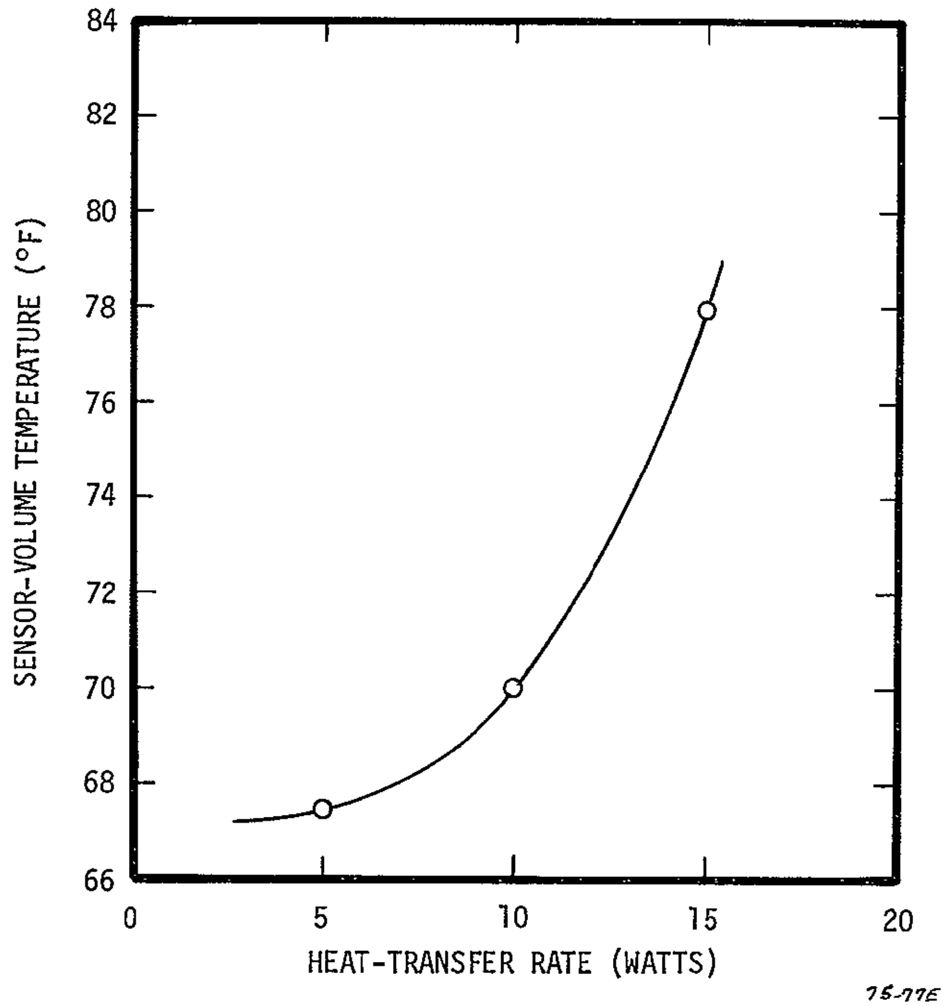

FIGURE 4-5. Set Point as Function of Load for 40F Sink.

Another characteristic of this heat pipe is that at a given heat-transfer rate, the set point increased with decreasing sink temperature There are two contributing factors First, when the valve shuts down, the temperature of the bellows/valve subassembly is set by conduction to approximately the temperature of the vapor in the condenser heat pipe The volume of control liquid around the bellows is significant and when the temperature of the heat sink drops the liquid around the bellows cools and contracts, which closes the valve The increased dry out results in an increased temperature difference between the heat pipes A second factor contributes to set-point dependence on sink temperature When the sink temperature is lowered, the viscosity of the returning liquid increases and results in a flow-induced increase in dry out

Figure 4-6 displays the dependence of set-point temperature on condenser vapor temperature Note that the flow-rate dependence is more pronounced at low condenser vapor temperatures where the viscosity is relatively high In fact, for a sufficiently low vapor temperature the control range is exceeded for 10 w, which is seen in the data at 11 00 on 4/2/75

The last feature of the heat pipe to be tested was the set-point control mechanism The sink was set at 15F and the heat load set at 10 w At 11 15 the sensor-volume temperature equilibrated at 75F The set-point screw was turned in one turn, which advances it 0 635 mm, and the sensor volume re-equilibrated at 67 5F, or a change of 6 5F per turn The screw was then turned out two turns and the sensor volume re-equilibrated at 81F, which corresponded to 6 75F per turn These values approximate the preliminary design calculation of 8 3F per turn

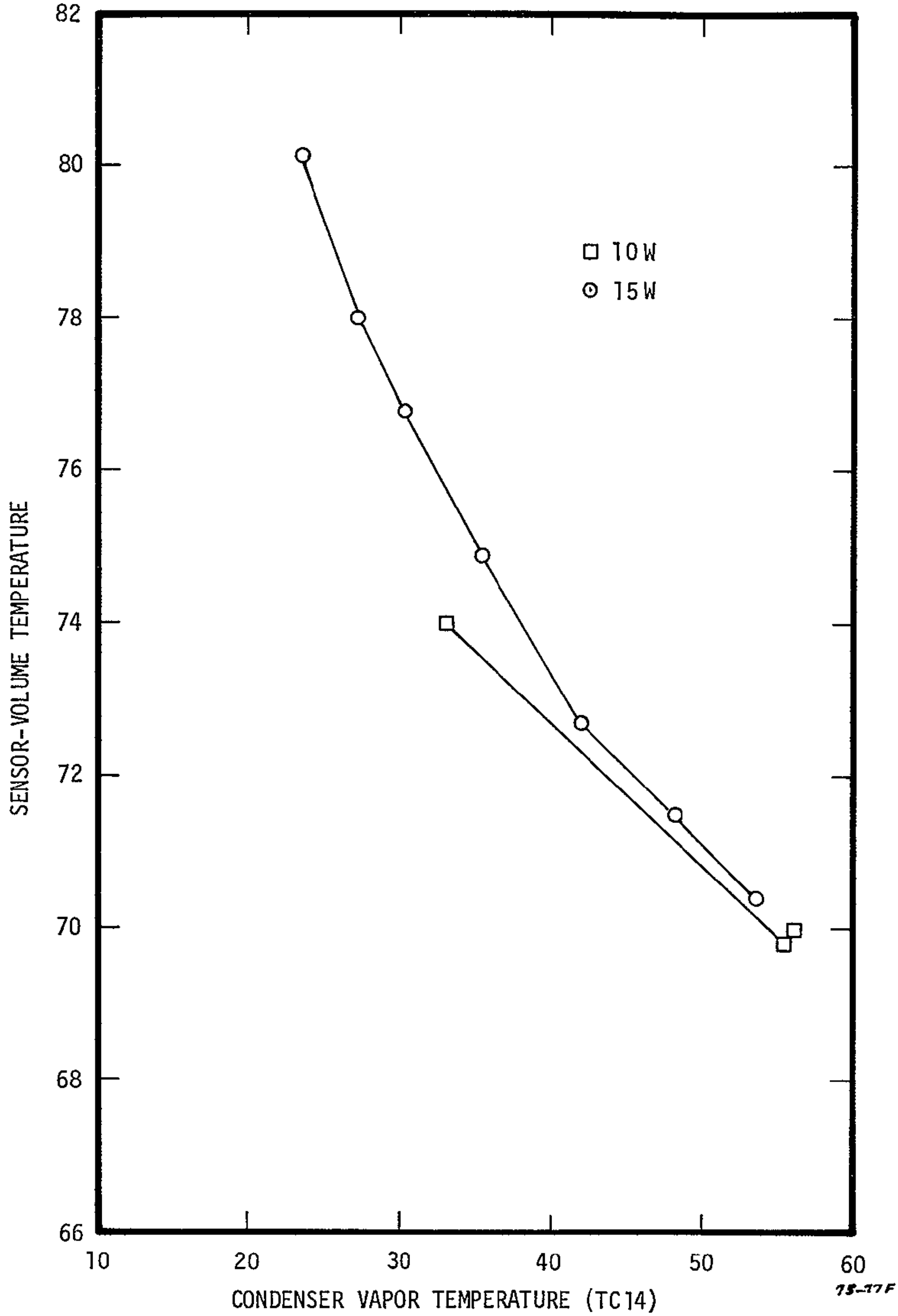

FIGURE 4-6 Effect of Condenser Heat-Pipe Vapor Temperature on Set Point

5 0 CONCLUSIONS AND RECOMMENDATIONS

A vapor-modulated heat pipe in which the pressure difference across a valve induces capillary groove and wick dry out in an evaporation region has been fabricated and tested The control valve is directly coupled to a sensor which can be located at the source to be controlled The vapor-modulated heat pipe tested was stainless steel with methanol as the working fluid

The principle conclusions of this effort were

1 The pressure-induced groove and wick dry out concept for heat pipe control is a means of avoiding the blow through limit of conventional vapor modulation techniques

2 A test article was fabricated and tested which verified successful operation of the major elements of this new heat pipe control technique

Several problems were uncovered, however, which we list below

1 Low capacity especially at low vapor temperatures of the condenser heat pipe

2 Gas generation

3 Change of set point with power and sink conditions

4 Temperature overshoot and steady-state oscillations in some cases

The primary design change would be to use a three heat pipe system with ammonia instead of two with methanol Two conventional heat pipes would be coupled by a third vapor-modulated heat pipe The coupling heat pipe will have optimized hydrodynamic performance, which includes a larger wick cross-section and a redesigned low-flow-resistance wick feed-through In addition, the bellows can well be mounted directly on the end of the evaporator heat pipe The sensor volume should have internal fins to minimize the thermal lag of the control liquid The new design offers the following advantages

- Greatly increased capacity due to short effective length of coupler heat pipe (6-inch compared to 27 5-inches of present heat pipe), switch to ammonia and optimized hydrodynamics
- Minimum set-point dependency on heat-transfer rate because coupler section will operate well below its open-valve dry-out limit
- Reduced sensitivity to gas because ammonia is a high-pressure fluid
- Small overall open-valve temperature drop because of high thermal conductivity of ammonia even with introduction of another evaporation and condensation surface
- Control liquid surrounding bellows is conductively coupled to evaporator heat pipe which has a relatively stable temperature Therefore, set point not affected by variations of condenser vapor temperature
- Reduced time to reprime when valve opens and reduced thermal lag of control fluid should reduce tendency for temperature overshoot and control volume oscillations

6 0 REFERENCES

1. Marcus, B D , "Theory and Design of Variable Conductance Heat Pipes," NASA CR-2018, 1972

2 Marcus, B D , Edwards, D K , and Anderson, W T , "Variable Conductance Heat Pipe Technology," Research Report No 4, NASA CR-114686, 1973

3 Eninger, J E , "Menisci Coalescence As A Mechanism For Venting Noncondensable Gas From Heat Pipe Arteries," AIAA Paper No 74-748, 1974

4 Eninger, J. E , "Capillary Flow-Through Heat Pipe Wicks," AIAA Paper No 75-661, 1975

APPENDIX

CONTENT OF APPENDIX

SK	REVISIONS			
	LTR	DESCRIPTION	DATE	APPROVED

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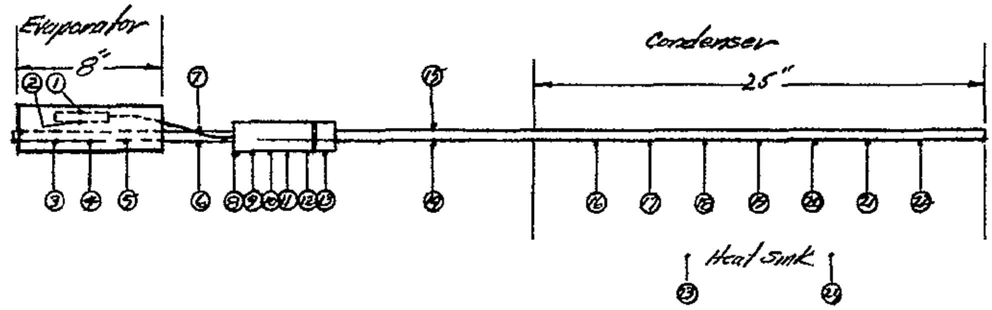
Top View



Thermocouple	Dist from Evap End
1	} on either side of control vol
2	
3	2.0
4	4.0
5	6.0
6	10.0
7	10.0
8	12.0
9	13.0
10	14.0
11	15.0
12	16.0
13	17.0
14	23.0
15	23.0
16	32.0
17	35.0
18	38.0
19	41.0
20	44.0
21	47.0
22	50.0

Note 1 High-limit Tc on control volume

2. Heat sink TC's 8" & 16" from condenser end

3 Use 6 mil teflon tape between evap saddle & heat pipe

4 Use RTV between control volume & evaporator saddle and on all condenser heat-transfer interfaces

ENGINEERING SKETCH

TRW SYSTEMS GROUP
ONE SPACE PARK • REDONDO BEACH CALIFORNIA

ORIGINATOR: Jim Eninger

DATE: 3/24/75

Instrumentation for VMHP

FIGURE 1

MJO

SIZE	CODE IDENT NO	
A	11982	SK 750324E

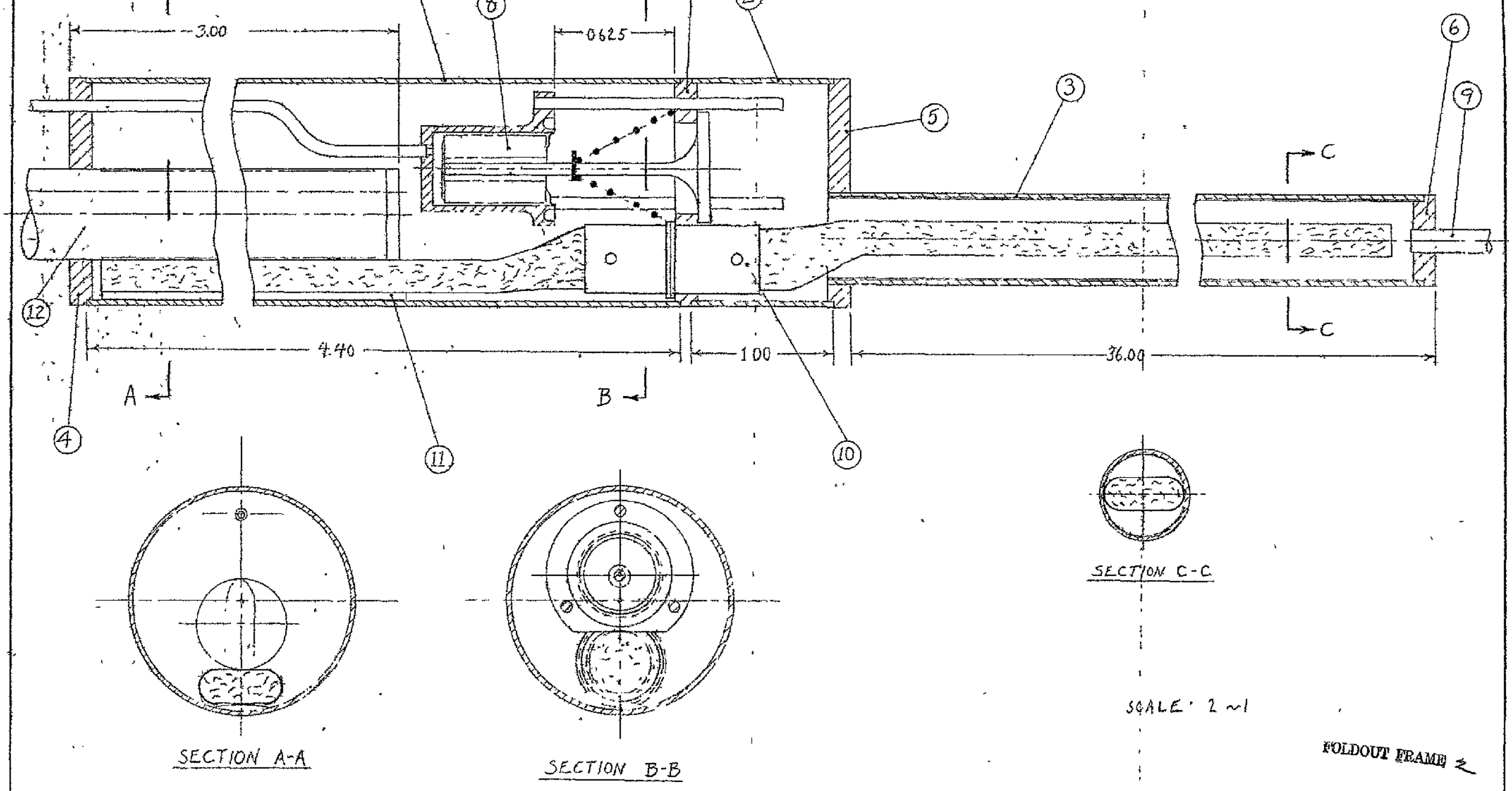
SCALE

SHEET 1 OF

SYSTEMS 523 REV 12-71

SK | CHG LTR

26263-6015-RU-00



FOLDOUT FRAME 2

FOLDOUT FRAME 1

ORIGINATOR	DATE	TITLE	
MJO	9/16/74	VAPOR MODULATED HEAT PIPE ASSEMBLY (VMHP)	ENGINEERING SKETCH TRW SYSTEMS GROUP ONE SPACE PARK REDONDO BEACH CALIFORNIA SK 740903 SHEET OF

SK	REVISIONS			26263-6015-RU-00
	LTR	DESCRIPTION	DATE	APPROVED

ITEM	PART NO.	QTY	DESCRIPTION	MATERIAL	SPEC
12	SK740915	1	EVAPORATOR SUB-ASSEMBLY	——	——
11	SK740914	1	FLAT SPRING 0.007 THK SHIM STOCK	STAINLESS STEEL 302	
10	SK740910	1	WICK SUB-ASSEMBLY	——	——
9	SK740905-3	1	FILL TUBE 1/8 OD X 0.020 WALL X 2.00	STAINLESS STEEL 304	
8	SK740907	1	VALVE SUB-ASSEMBLY	——	——
7	SK740906	1	BULKHEAD 1-1/4" ROD STOCK	STAINLESS STEEL 304	
6	SK740905-2	1	END CAP 1/2" DIA ROD	STAINLESS STEEL 304	
5	SK740904-2	1	END CAP 1/8 THK SHEET	STAINLESS STEEL 304	
4	SK740904-1	1	END CAP 1/8 THK SHEET	STAINLESS STEEL 304	
3	SK741001-3	1	TUBE, THREADED 1/2 OD X 0.035 WALL	STAINLESS STEEL 304	SP-13B-02
2	—	1	TUBE 1 1/4 OD X 0.028 WALL	STAINLESS STEEL 304	
1	—	1	TUBE 1 1/4 OD X 0.028 WALL	STAINLESS STEEL 304	

PARTS LIST

ENGINEERING SKETCH

TRW
SYSTEMS GROUP
ONE SPACE PARK • REDONDO BEACH CALIFORNIA

ORIGINATOR	DATE	
	9/16/74	VAPOR MODULATED HEAT PIPE (VMHP) PARTS LIST
MJO		

SIZE	CODE IDENT NO	
A	11982	SK 740903
SCALE		SHEET 1 OF

SYSTEMS 523 REV 12-71

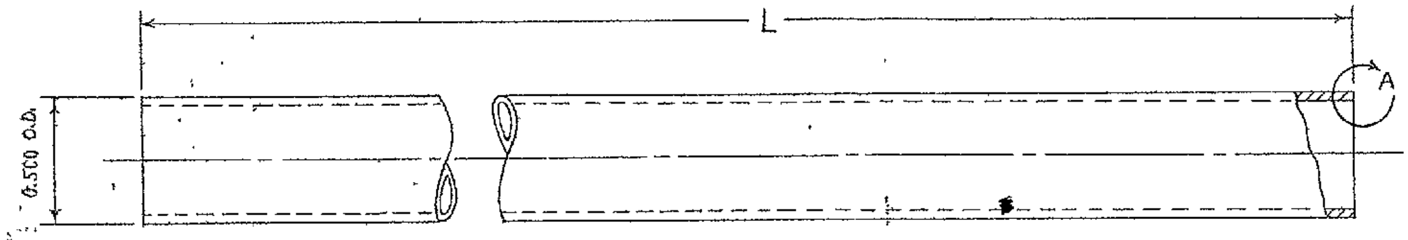
26263-6015-RU-00

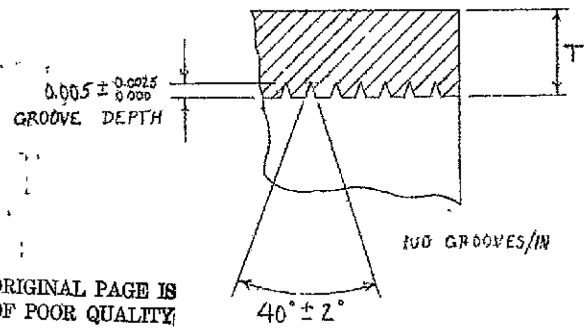
SK | CHG LTR

NOTES

1. TUBE I.D. TO CONFORM TO REQUIREMENTS OF SPEC SP-13B-02.
2. INTERNAL GROOVES ENTIRE LENGTH PER SPEC. SP-13B-02.

DASH NO.	L	T (STK.)
-1	35.75	0.035
-2	23.55	0.035
-3	35.88	0.035
-4	70.86	0.035
-5	38.58	0.028





DETAIL A (20 ~ 1)

C	PH15-7 Mo S.S.
B	304 CRES
A	6061-T6 AL
LETTER	MATERIAL

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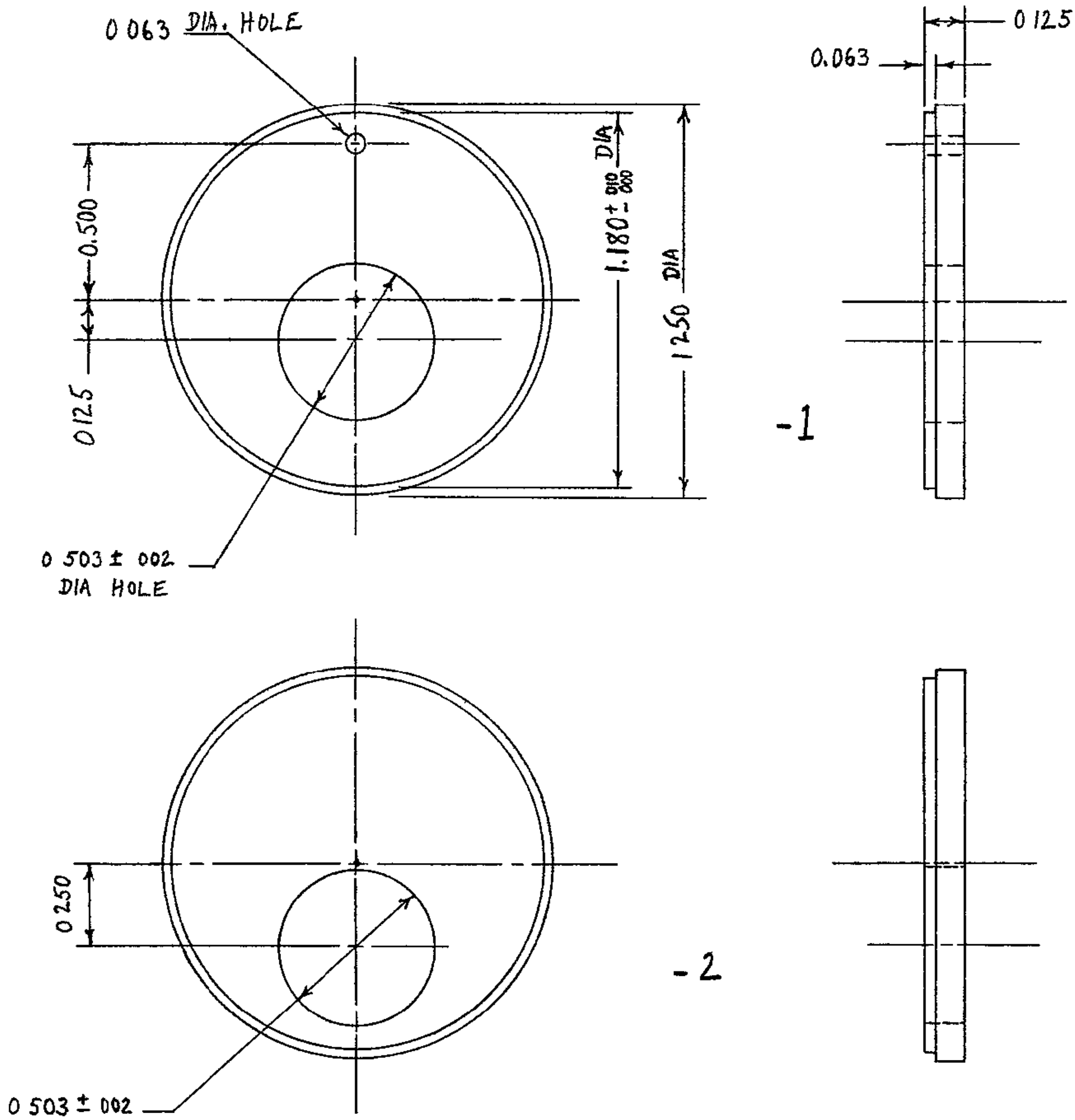
FOLDOUT FRAME 1

FOLDOUT FRAME 1

ORIGINATOR	DATE	TITLE	ENGINEERING SKETCH
G FLEISCHMAN	10-1-74	TUBE, GROOVED	TRW SYSTEMS GROUP ONE SPACE PARK REDONDO BEACH, CALIFORNIA
			SK 741001
MJO			SHEET OF

SYSTEMS 5238 REV 5-67

SK	REVISIONS			26263-6015-RU-00
	LTR	DESCRIPTION	DATE	APPROVED



-2 SAME AS -1, EXCEPT AS NOTED.

ENGINEERING SKETCH

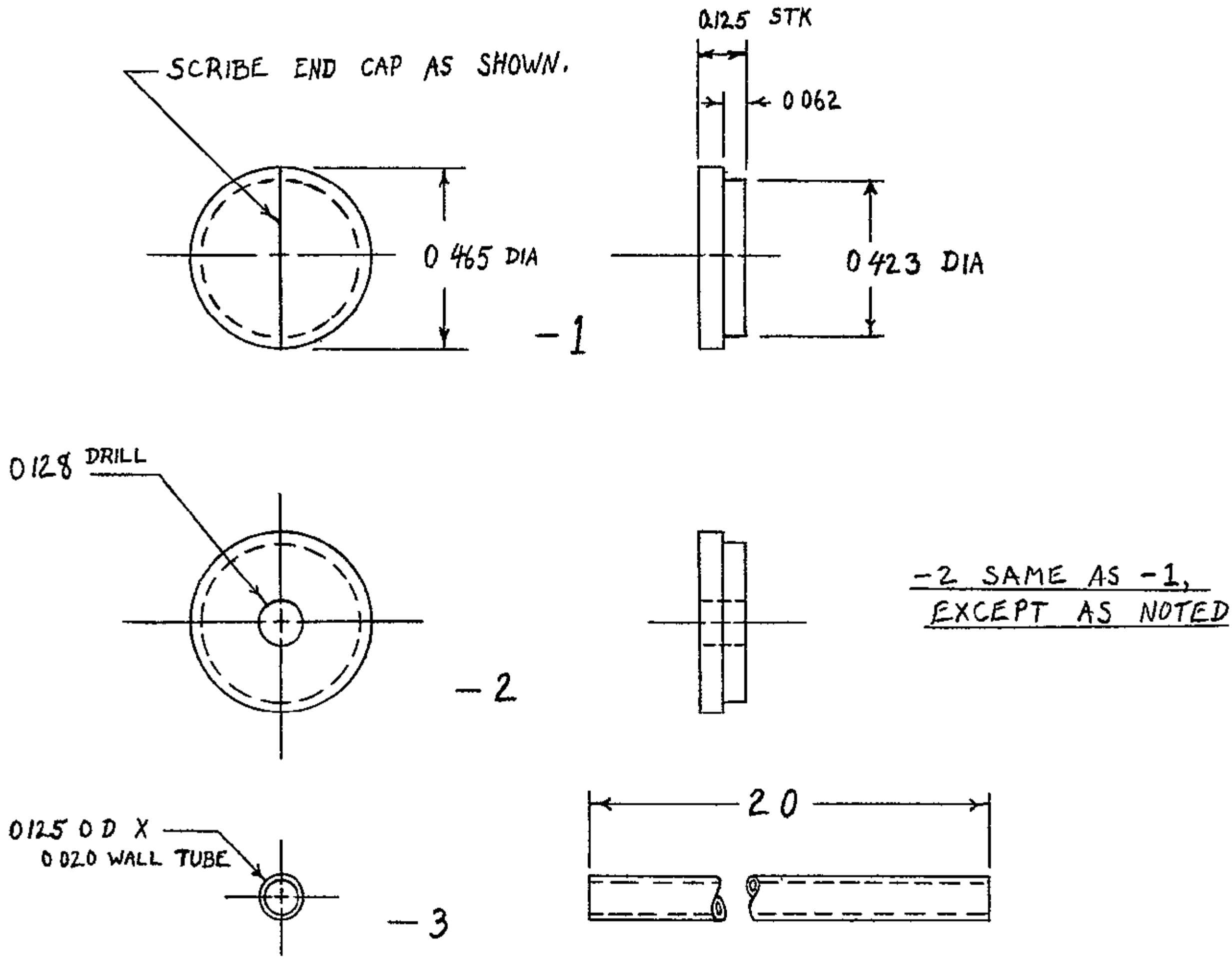
TRW SYSTEMS GROUP
ONE SPACE PARK • REDONDO BEACH CALIFORNIA

ORIGINATOR	DATE	
	9/16/74	VMHP END CAP
MJO		

SIZE	CODE IDENT NO	
A	11982	SK 740904
SCALE 2~1		SHEET 1 OF

SYSTEMS 523 REV 12 71

SK	REVISIONS			26263-6015-RU-00
	LTR	DESCRIPTION	DATE	APPROVED



PART NO.	DESCRIPTION	MATERIAL
SK740905-3	FILL TUBE	304 CRES TUBE, 0.125 O.D X 0.020 WALL
SK740905-2	END CAP	304 CRES ROD, 1/2" DIA
SK740905-1	END CAP	304 CRES ROD, 1/2" DIA

ENGINEERING SKETCH

TRW SYSTEMS GROUP
ONE SPACE PARK • REDONDO BEACH CALIFORNIA

ORIGINATOR	DATE
G FLEISCHMAN	10/18/74

MJO

END CAPS AND FILL TUBE

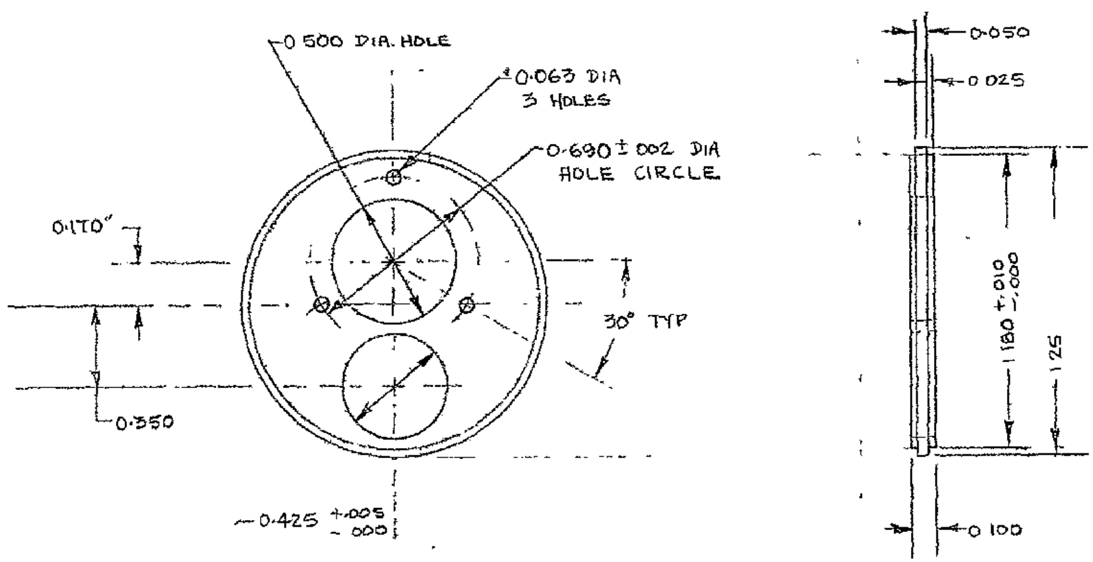
SIZE	CODE IDENT NO	
A	11982	SK 740905

SCALE 2~1 | SHEET 1 OF

SYSTEMS 523 REV 12 71

SK | CHG LTR

26263-6015-RU-00



FOLDOUT FRAME 2

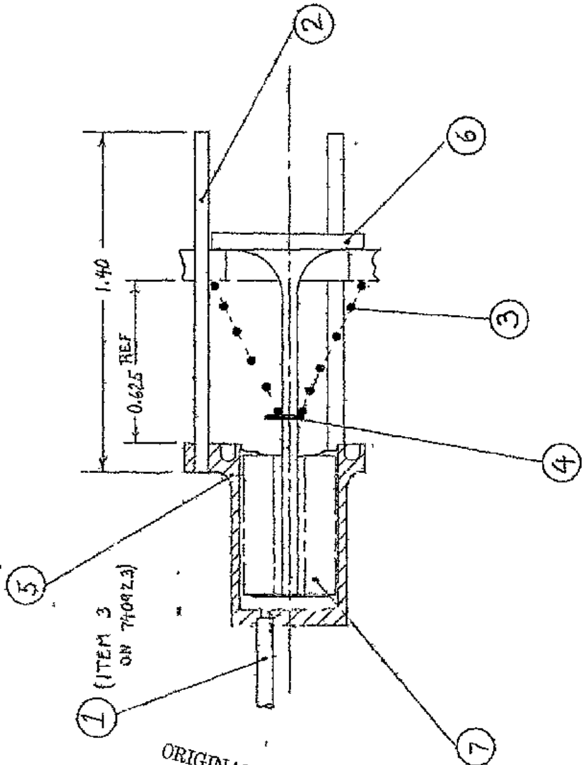
ORIGINATOR	DATE	TITLE	ENGINEERING SKETCH
	10/12/74	VMHP BULKHEAD	TRW SYSTEMS GROUP ONE SPACE PARK REDONDO BEACH, CALIFORNIA
MJO			SK 740906
			SHEET OF

SYSTEMS 8238 REV. 5-67

FOLDOUT FRAME 1

SK

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED



FOLDOUT FRAME

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OF POOR QUALITY

ENGINEERING SKETCH

TRW SYSTEMS GROUP
ONE SPACE PARK • REDONDO BEACH CALIFORNIA

ORIGINATOR | DATE

MJO

SIZE A | CODE IDENT NO 11982 | SK

SCALE | SHEET 1 OF

SYSTEMS 523 REV. 12-71

SK

REVISIONS 26263-6015-RU-00

LTR	DESCRIPTION	DATE	APPROVED

PARTS LIST

ITEM	PART NO	QTY	DESCRIPTION	MATERIAL	SPEC.
7	——	1	BELLOWS METAL BELLOWS COMPANY	STAINLESS STEEL 347	
6	SK740909	1	VALVE 5/8 DIA. ROD	STAINLESS STEEL 304	
5	SK740908	1	BELLOWS CAN 7/8 DIA. ROD	STAINLESS STEEL 304	
4	——	1	RETAINING RING TRUARC	STAINLESS STEEL (PH 15-7 Mo)	Y5133-6H
3	——	1	CONICAL SPRING PARAGON SPRING COMPANY	STAINLESS STEEL 302	C-4467 (P/N 9474)
2	——	3	VALVE GUIDE 1/16 DIA. ROD X 1.40"	STAINLESS STEEL 304	
1	——	1	SENSOR FEEDTUBE 1/16 O.D X 0.020 WALL X 2.40"	STAINLESS STEEL 304	

ENGINEERING SKETCH

TRW SYSTEMS GROUP
ONE SPACE PARK • REDONDO BEACH CALIFORNIA

ORIGINATOR | DATE 9/17/74

VMHP
VALVE SUB-ASSEMBLY

FOLDOUT FRAME 2

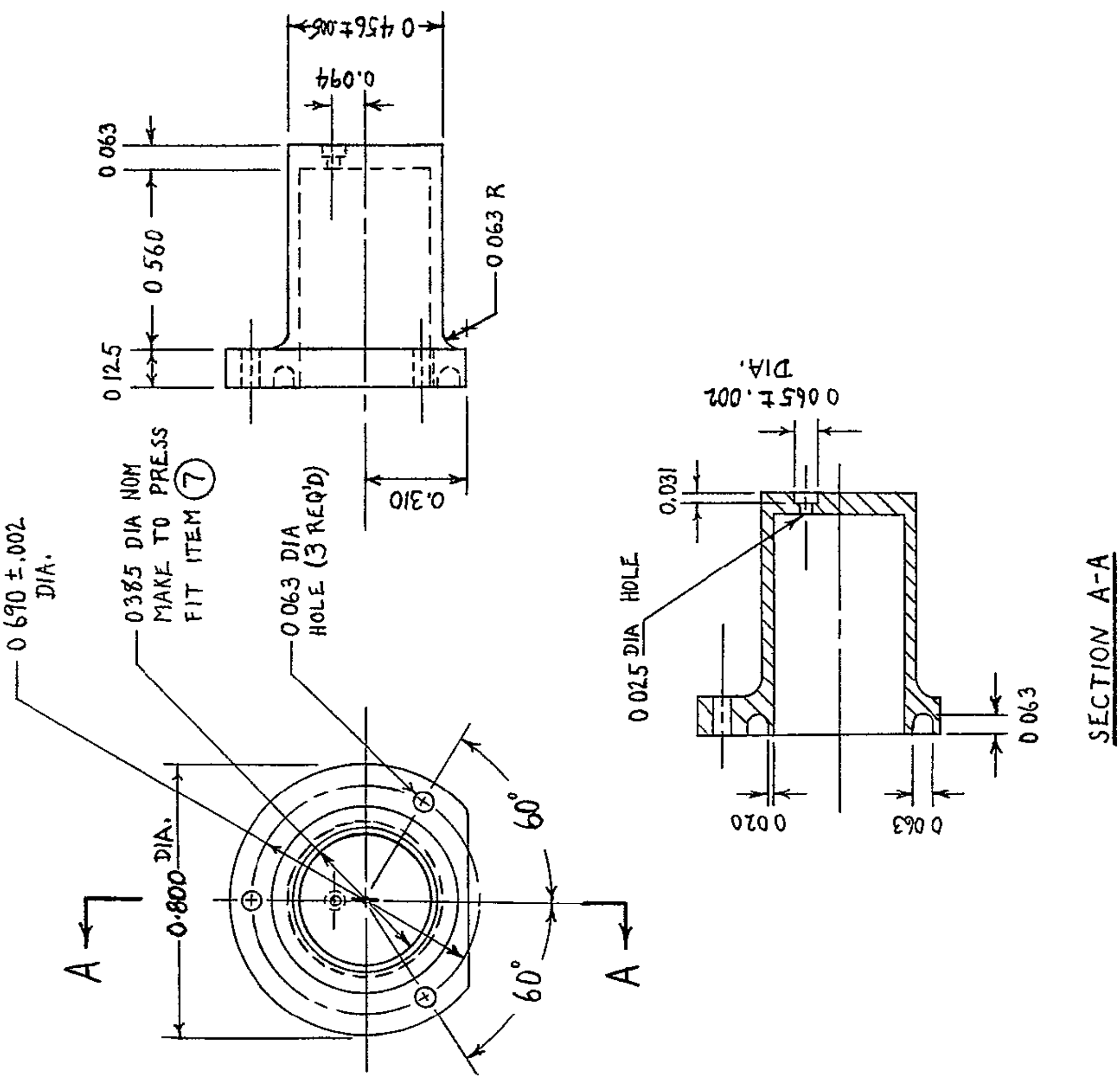
MJO

SIZE A | CODE IDENT NO 11982 | SK 740907

SCALE 2~1 | SHEET 1 OF

SYSTEMS 523 REV. 12-71

SK	REVISIONS			26263-6015-RU-00
	LTR	DESCRIPTION	DATE	APPROVED

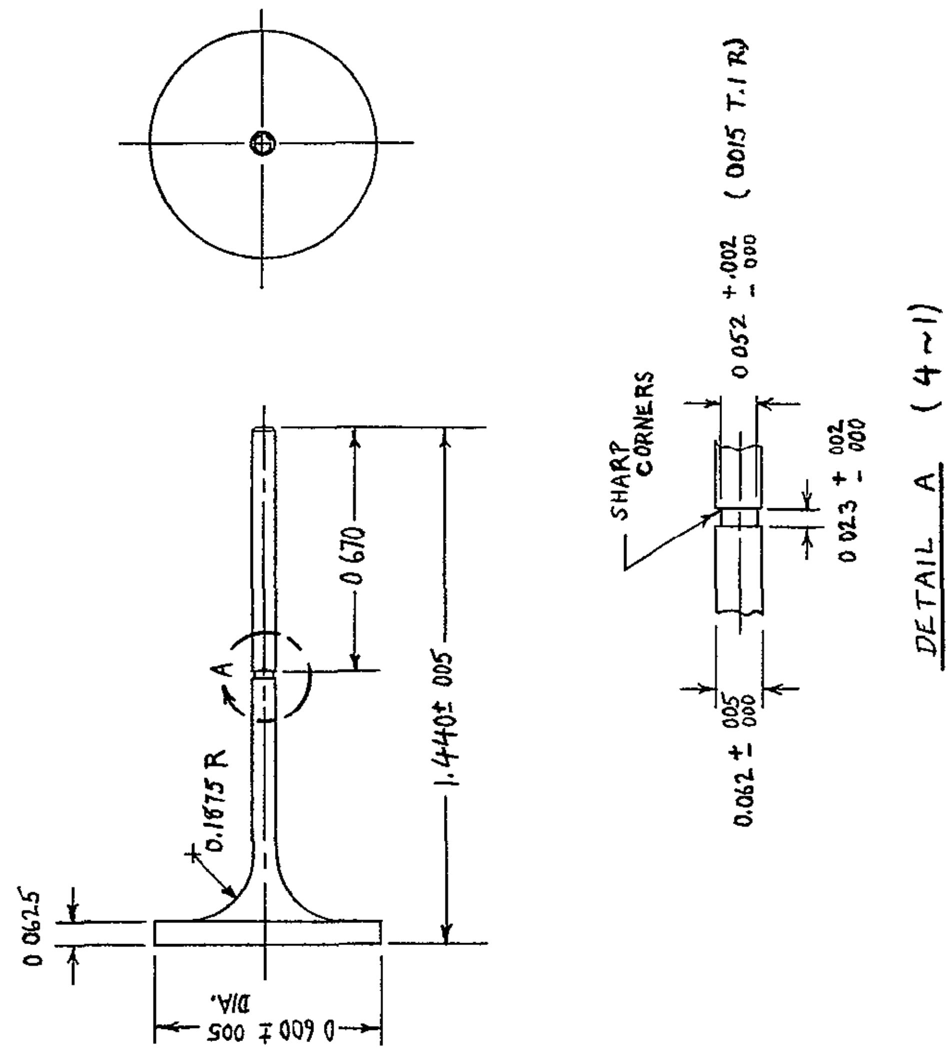


ENGINEERING SKETCH		TRW SYSTEMS GROUP ONE SPACE PARK • REDONDO BEACH CALIFORNIA		
ORIGINATOR	DATE 9/17/74	VMHP BELLOWS CAN		
		SIZE A	CODE IDENT NO 11982	SK 740908
MJO		SCALE 2 ~ 1		SHEET 1 OF

SYSTEMS 523 REV 12 71

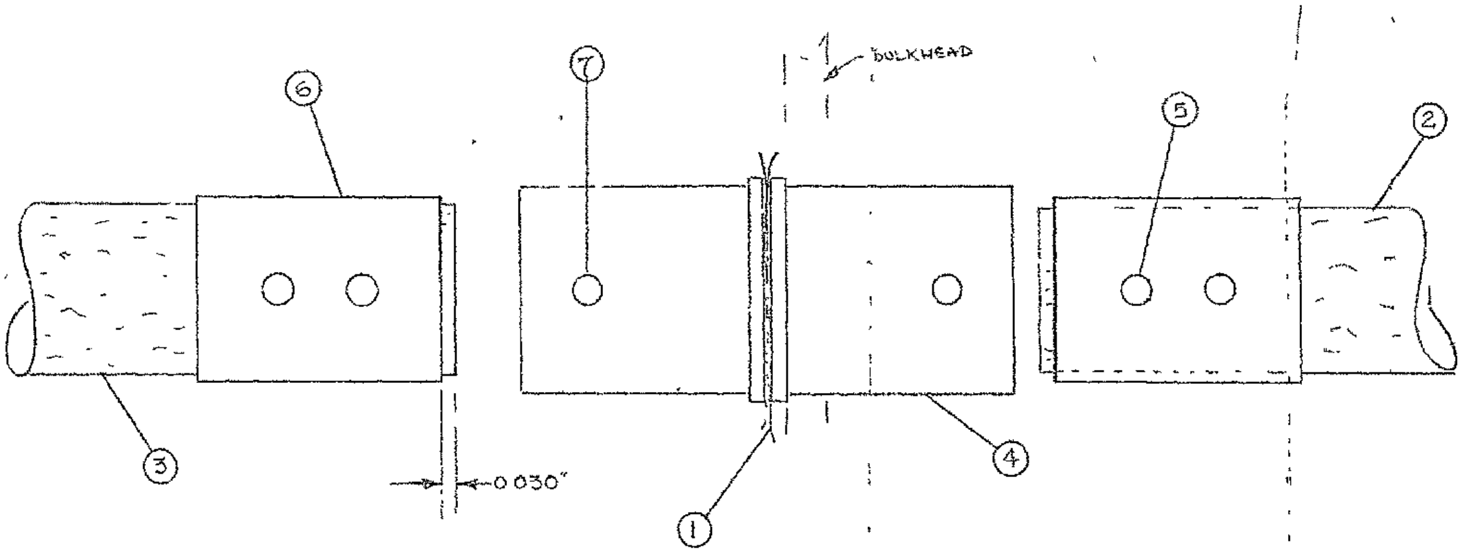
SK

REVISIONS			26263-6015-RU-00
LTR	DESCRIPTION	DATE	APPROVED



ENGINEERING SKETCH		TRW SYSTEMS GROUP ONE SPACE PARK • REDONDO BEACH CALIFORNIA		
ORIGINATOR	DATE 9/9/74	VMHP VALVE		
		SIZE A	CODE IDENT NO 11982	SK 740909
MJO		SCALE 2~1		SHEET 1 OF

SYSTEMS 523 REV 12 71



ASSEMBLY NOTES

1. INSERT WICK ③ & ② INTO WICK CLAMP SO THAT PIN HOLES ARE PARALLEL TO WIDEST WICK DIMENSION
2. EXTEND WICK BEYOND WICK CLAMP BY ~.1", DRILL THRU & INSERT PIN ⑤
3. USE FIXTURE TO CUT WICK EXTENSION TO 0.030"
4. CLAMP WICK TUNNEL PARTS TOGETHER, ALIGN PIN HOLES, WELD AT SCREEN-WICK TUNNEL INTERFACE

ITEM	PART NO.	QTY	DESCRIPTION	MATERIAL	[illegible]
7	740913-2	2	WICK CLAMP PIN	CRES 304	
6	740913	2	WICK CLAMP	CRES 304	
5	740913-1	4	[illegible] PIN	[illegible]	
4	[illegible]	2	[illegible] TUNNEL	[illegible]	
3	[illegible]	1	[illegible]	[illegible]	[illegible]-2
2	[illegible]	1	[illegible]	[illegible]	[illegible]903-2
1	—	2	[illegible]	[illegible]	

PARTS LIST

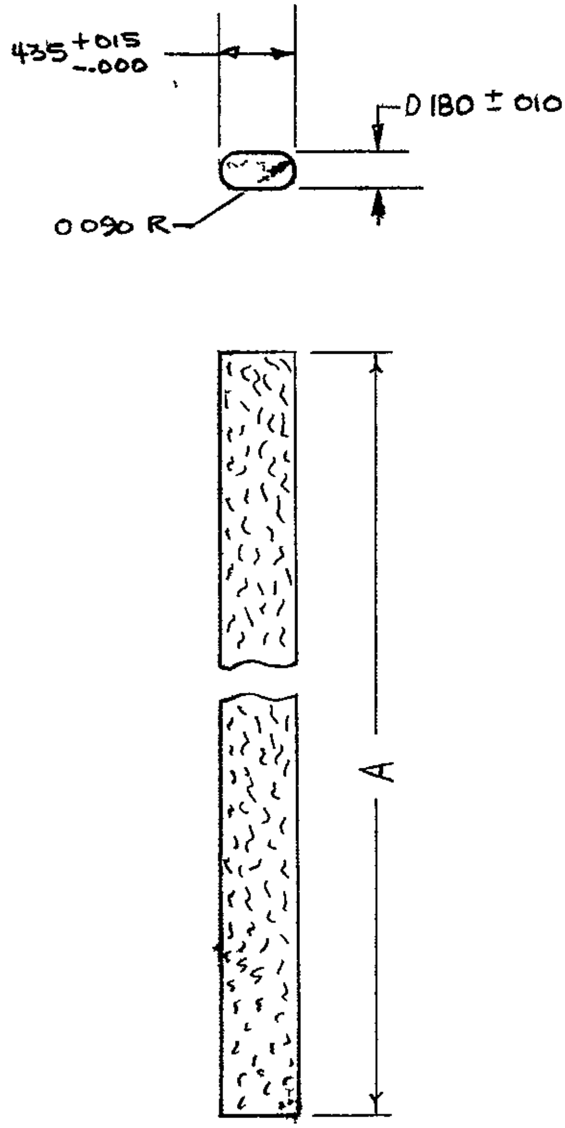
ORIGINATOR	DATE 10/13/74	TITLE VMHP WICK SUB-ASSEMBLY	ENGINEERING SKETCH TRW
MJO			SK 740910
			SHEET 2 OF 3

FOLDOUT FRAME 1

FOLDOUT FRAME 2

SK	REVISIONS			26263-6015-RU-00
	LTR	DESCRIPTION	DATE	APPROVED

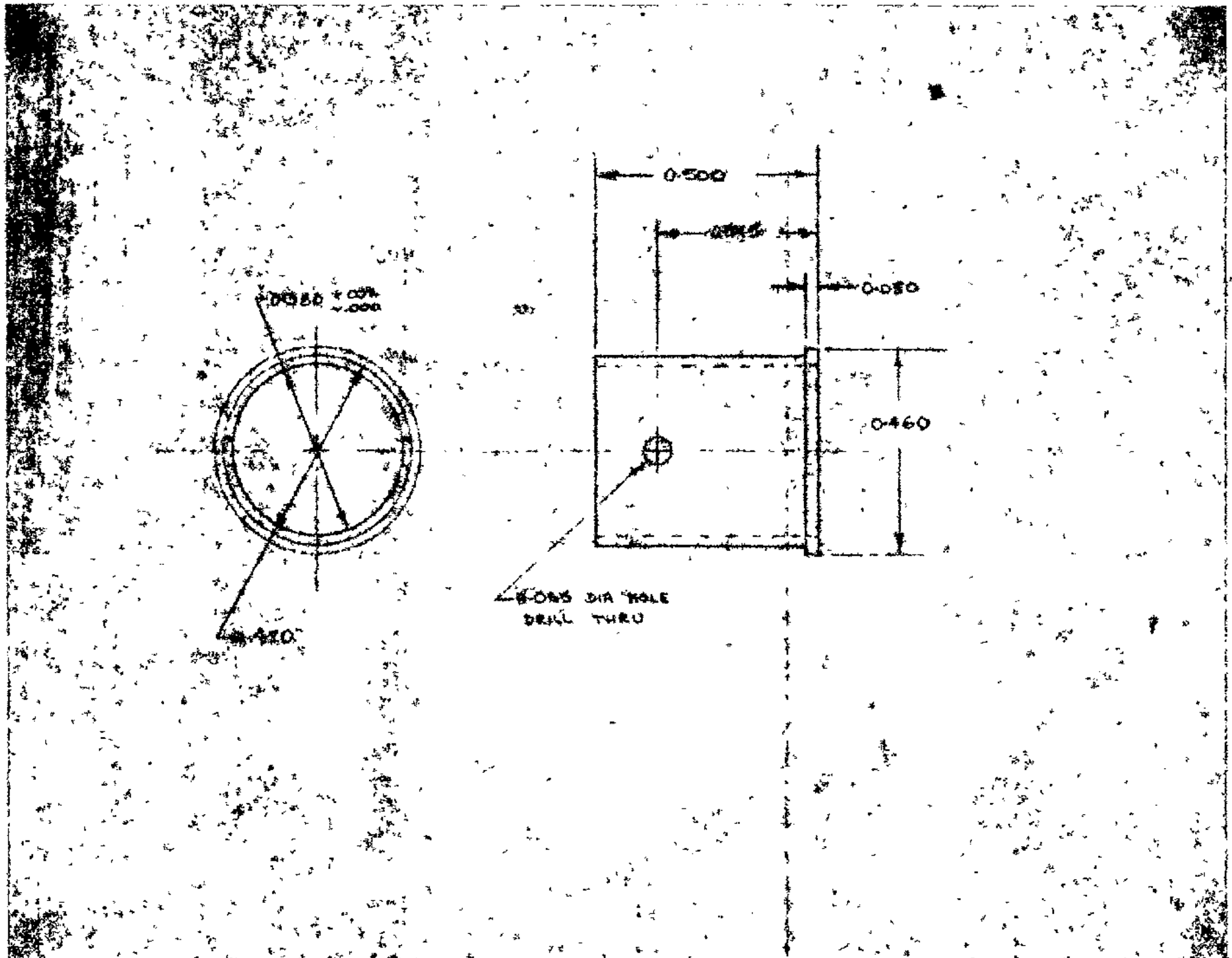
DASH NO	A
-1	38.0
-2	5.0



NOTE DIMENSION "A" INCLUDES EXCESS TO BE TRIMMED AFTER INSTALLATION

ENGINEERING SKETCH		TRW SYSTEMS GROUP ONE SPACE PARK • REDONDO BEACH CALIFORNIA		
ORIGINATOR	DATE 9/19/74	VMHP WICK		
		SIZE A	CODE IDENT NO 11982	SK 740911
MJO		SCALE 2~1		SHEET 1 OF

SYSTEMS 523 REV 12-71



SCALE 4~1

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FOLDOUT FRAME 1

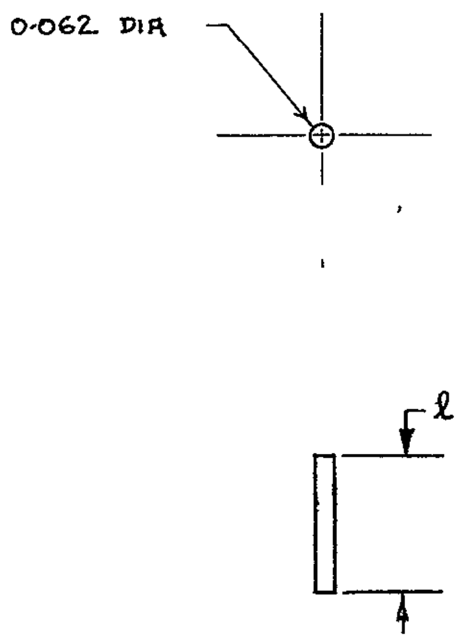
FOLDOUT FRAME 2

ORIGINATOR	DATE	TITLE	ENGINEERING SKETCH
E E LUEDKE	10/22/74	VMHP WICK TUNNEL	TRW
			SK 740912
MJO			SHEET OF

SK

REVISIONS			26263-6015-RU-00
LTR	DESCRIPTION	DATE	APPROVED

DASH NO.	LENGTH - ℓ - in.
-1	0.375
-2	0 420



ENGINEERING SKETCH

TRW
SYSTEMS GROUP
ONE SPACE PARK • REDONDO BEACH CALIFORNIA

ORIGINATOR	DATE
	9/19/74
MJO	

VMHP
WICK PIN

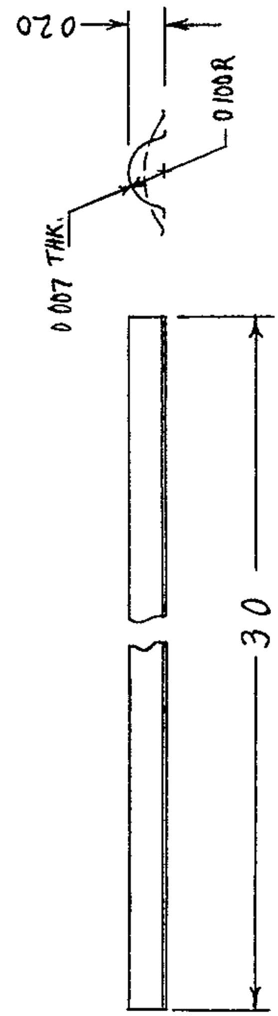
SIZE	CODE IDENT NO	
A	11982	SK 740913

SCALE 2~1		SHEET 1 OF

SYSTEMS 523 REV 12 71

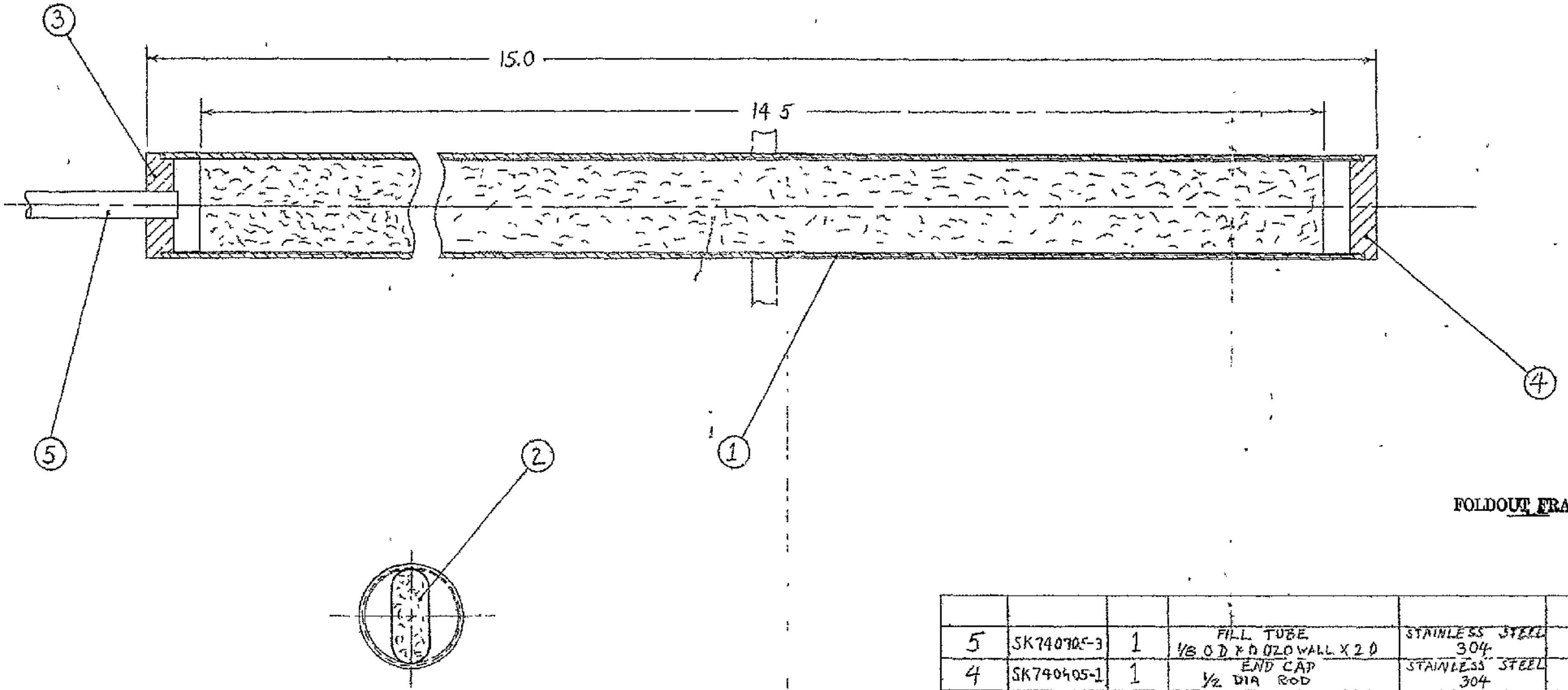
SK

REVISIONS			26263-6015-RU-00
LTR	DESCRIPTION	DATE	APPROVED



ENGINEERING SKETCH		TRW SYSTEMS GROUP ONE SPACE PARK • REDONDO BEACH CALIFORNIA	
ORIGINATOR	DATE 9/19/74	VMHP FLAT SPRING	
		SIZE A	CODE IDENT NO 11982	SK 740914
MJO		SCALE 2 ~ 1	SHEET 1 OF

SYSTEMS 523 REV 12 71



FOLDOUT FRAME 2

ITEM	PART NO	QTY	DESCRIPTION	MATERIAL	SPEC.
5	SK740905-3	1	FILL TUBE 1/8 OD X 0 020 WALL X 2 0	STAINLESS STEEL 304	
4	SK740905-1	1	END CAP 1/2 DIA ROD	STAINLESS STEEL 304	
3	SK740905-2	1	END CAP 1/2 DIA ROD	STAINLESS STEEL 304	
2	SK 1003-2	1	EVAPORATOR WICK (21% DENSITY, 0.75 WIDE)	STAINLESS STEEL 304	SK 1003-2
1	SK740916	1	TUBE, THREADED 1/2 OD X 0 035 WALL	STAINLESS STEEL 304	SP-13B-02

PARTS LIST

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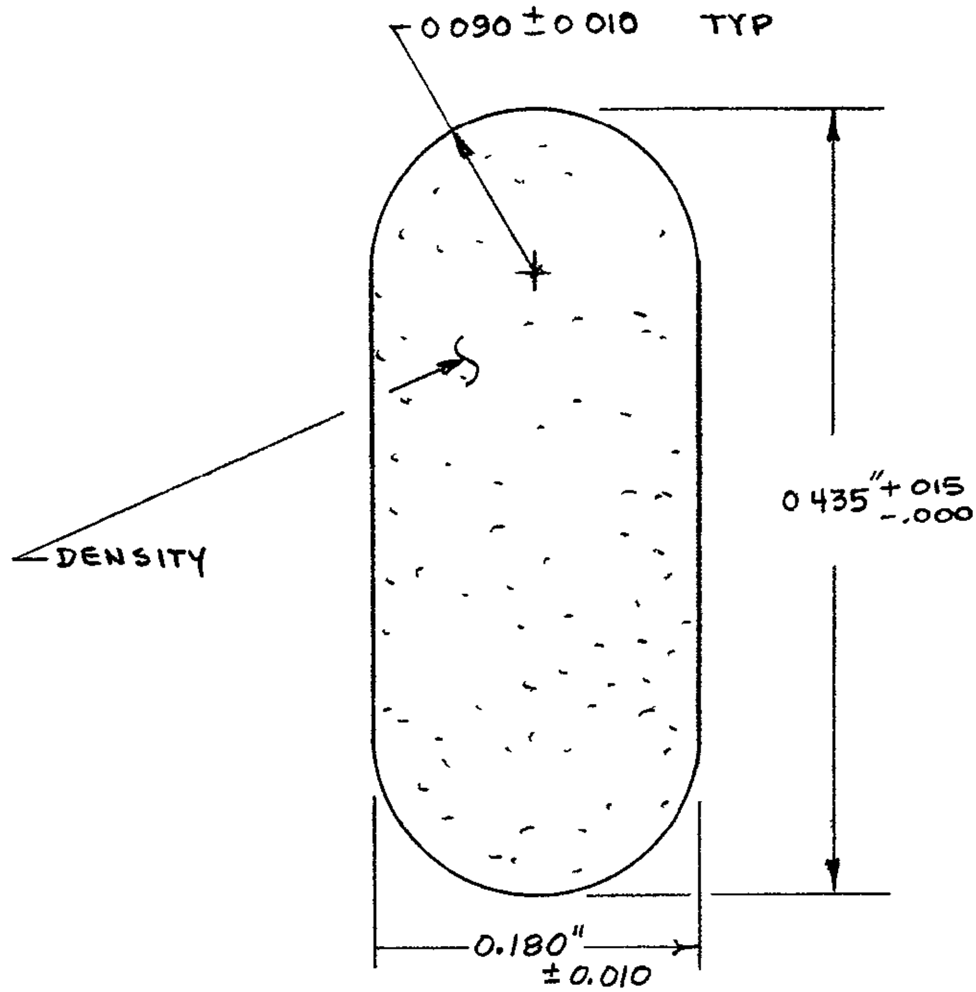
ORIGINATOR	DATE	TITLE	ENGINEERING SKETCH
MJO	9/20/74	VMHP EVAPORATOR SUB-ASSEMBLY	TRW SYSTEMS GROUP ONE SPACE PARK · REDONDO BEACH CALIFORNIA
			SK 740915
			SHEET OF

FOLDOUT FRAME 1

SCALE: 2 ~1

SK 1003

REVISIONS			26263-6015-RU-00
LTR	DESCRIPTION	DATE	APPROVED



SK 1003-3	304 CRES WIRE, 0.0036 ± 0.0002 DIA.	24 ± 1 %
SK1003-2	304 CRES WIRE, 0.0050" ± 0.0002 DIA.	21 ± 1 %
SK 1003-1	5056 ALUMINUM WIRE, 0.0050" ± 0.0002 DIA.	21 ± 1 %
PART NO.	MATERIAL	WICK DENSITY

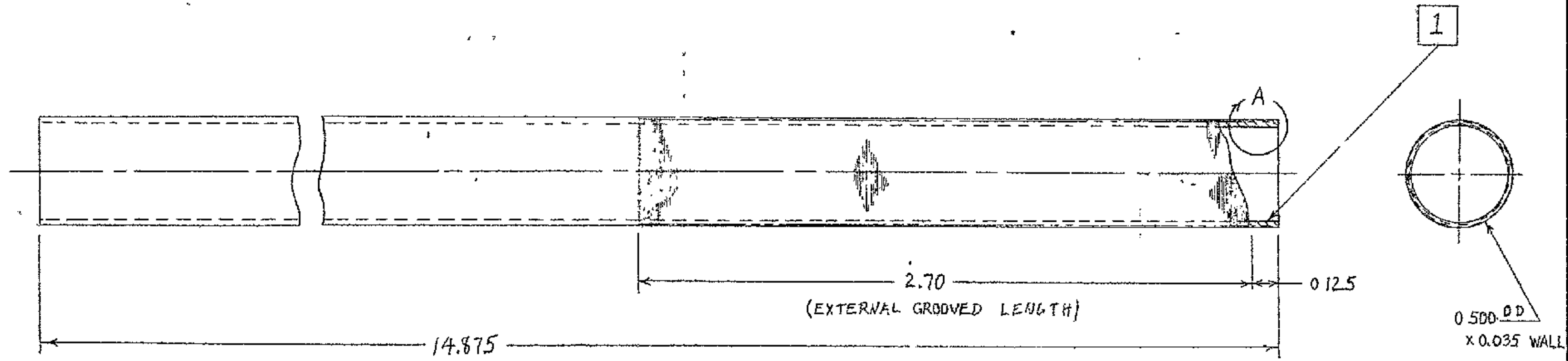
ENGINEERING SKETCH		TRW SYSTEMS GROUP ONE SPACE PARK • REDONDO BEACH CALIFORNIA	
ORIGINATOR EE LUEDKE	DATE 10/7/74	HOMOGENEOUS WICK	
MJO		SIZE A	CODE IDENT NO 11982
		SK 1003	
		SCALE	SHEET 1 OF

SYSTEMS 523 REV 12-71

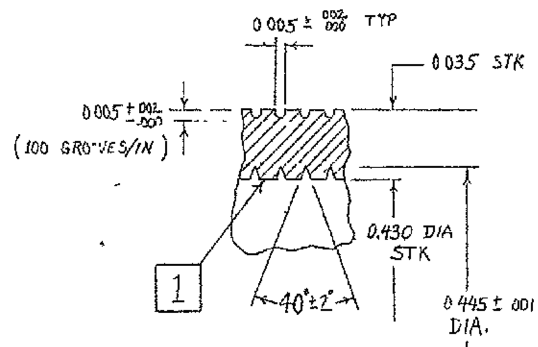
SK | CHG LTR

NOTES

1 INTERNAL GROOVES ENTIRE LENGTH PER SPEC. SP-13B-02.



SCALE 2~1



DETAIL A (20~1)

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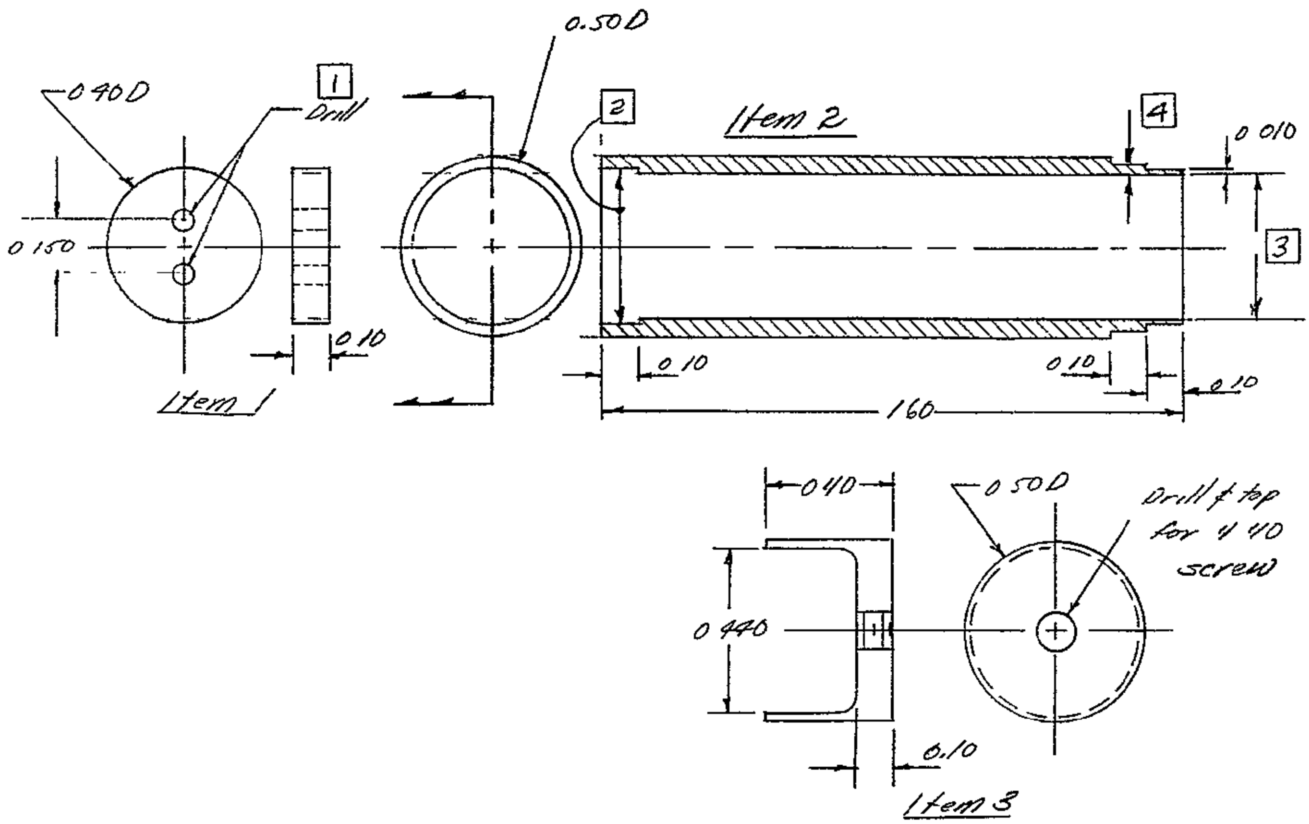
FOLDOUT FRAME 1

FOLDOUT FRAME 2

ORIGINATOR	DATE	TITLE	
	9/20/74	VMHP TUBE, THREADED	ENGINEERING SKETCH TRW SYSTEMS GROUP ONE SPACE PARK REDONDO BEACH, CALIFORNIA
MJO			SK 740916
			SHEET OF

SK	REVISIONS			26263-6015-RU-00
	LTR	DESCRIPTION	DATE	APPROVED



MATERIAL: 304 CRES

Notes:

4 Machine so Item 3 fits over shoulder

3 Machine so flange on supplied bellows fits snugly inside.

2 Machine to fit Item 1

1 Drill for snug fit of 0.063 OD tubing supplied

ENGINEERING SKETCH		TRW SYSTEMS GROUP ONE SPACE PARK • REDONDO BEACH CALIFORNIA		
ORIGINATOR Jim Eninger	DATE 3/10/74	Control Volume parts		
X 50370		SIZE A	CODE IDENT NO 11982	SK 750310E
MJO		SCALE		SHEET 1 OF

SYSTEMS 523 REV 12 71